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# An Overview of the Problems and Prospects for Circular Agriculture in Sustainable Food Systems in the Anthropocene

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## Abstract

In this overview paper, we outline and explore problems and prospects for circular agriculture's contributions to transformative change toward sustainable food systems in the Anthropocene. We define circular agriculture (CA) and provide historical context on its development. We then discuss how CA can contribute to food system transformations in four key areas: multi-functional landscapes; sustainable intensification (focusing on nitrogen/crop-livestock management and digital agriculture); smallholder farmers; and dietary change. We find that food systems transitions will be challenging due to the depth, scale, and speed of changes necessary for humans to remain within safe planetary boundaries out to 2050.

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## INTRODUCTION

### The State of Global Food Systems

In the modern era, humans have not often attempted to intentionally design a food system at any scale much beyond a local farm or limited region. In 2021, however, it is increasingly clear that profound transformation across multiple levels is required in how we produce and consume food if we are to stay within safe planetary boundaries on Earth[1,2,3]. This is evident from the scientific literature as well as recent reports on achieving sustainable food systems from major international organizations[4,5,6].

The common catch phrase in this literature is that fundamental, or transformative change is needed within our food systems, where 'transformative' means 'system-wide reorganization across technological, economic, and social factors, making sustainability the norm rather than the altruistic exception'[7]. In this sense, food systems include all elements (nature, people, institutions, governance) and actions (from production through consumption) along with their environmental, economic, and social outcomes[8,9]. This expansive definition is rooted in a social-ecological systems perspective on nature and people in which both environmental and human factors are considered in relation as they are mutually shaped by key drivers, interact across many scales, exhibit complex dynamics, respond to multiple feedbacks, and are subject to uncertainty and change over time[10].

If the goal of a sustainable food system is the delivery of food and nutritional security for all people over the long-term with limited environmental degradation, then the biophysical basis for transformative change is obvious. Croplands cover about one third of terrestrial land on Earth[11] and agricultural activities contribute about 26% of total global greenhouse gas emissions[12]. Food systems are the primary driver of biodiversity loss and ecological degradation[11], the largest contributor to freshwater consumption[1], and are major sources of multiple pollutants including nitrogen[13], phosphorus[14], heavy metals[15], antibiotics[16], and microplastics[17]. If all non-food greenhouse gas emissions ended immediately, food systems emissions alone would likely carry us beyond a 1.5C rise in global temperature soon after 2050[18].

Staying within safe planetary boundaries, however, is not just about the biophysical elements of food systems; the social aspects are equally important within a social-ecological framework. And, since 2014, in spite of six years of implementation of the food-oriented targets of the United Nations (UN) Sustainable Development Goals (SDGs), global food insecurity has been growing, with the number of hungry people reaching 690 million, about 9% of the human population[19].

The above data portray elements of food security before COVID-19. The number of additional undernourished people resulting from impacts from COVID-19 is modelled to increase 83-150 million by the end of 2021[20], and projections show that there may be up to 840 million hungry people by 2030[19]. Therefore, the virus is seen by many as a wake-up call that has brought social vulnerabilities into focus across multiple elements of food systems, including farmer and laborer vulnerability, global supply chains, import/export trade policy, and more[21,22]. Yet, as of the beginning of 2021, individual country responses to strengthen food systems have been minimal, despite multiple calls from international agencies and researchers to link food security measures with expanded support for public health.

As COVID-19 spotlights weaknesses in food systems, other trends continue to put inexorable pressure on conventional agricultural activities. Total greenhouse gas emissions are projected to increase at an annual average rate of 2−6% out to 2030 with major contributions from rising carbon-intensive livestock production, growing beef and dairy consumption, and continuing cropland expansion into natural ecosystems[23,24]. Longer-term trends appear to offer little relief. Out to 2050, the medium range projection for human population growth is 9.7 billion people, an increase of about 2 billion over 2020[25]. Over this period, some two billion people are expected to enter the global middle class with projections that they will use their increased wealth for more resource-intensive consumption, including eating many more animal products[26]. These two trends underlie projections for a 25−70% rise in global food production to meet demand to 2050[27].

Transformative change in food systems is uniquely challenging given the links between food as a source of physical and cultural sustenance and its commodification through heterogeneous systems of private and public economics, institutions, and governance. Fostering change in food systems requires more than technical innovation; it is about how culture and identity shape individual attitudes about food. And food systems transformation is also about political decisions that influence policy, institutions, and governance[28].

In response to these challenges, current food systems research is expanding to address links within and beyond how crops are grown in fields to the full range of agriculture practices within tele-coupled food systems in the 21st century[29]. However, even as concomitant understanding of the ecological and social sides of food systems is growing, coordinated research and international policy remains missing.

In this broad overview paper, we briefly outline and explore critical problems and promising prospects for circular agriculture's contributions to transitions to sustainable food systems in the Anthropocene. We define circular agriculture (CA) and provide historical context on its development. We then consider how CA may contribute to food system transformations in four key areas: multi-functional landscapes; sustainable intensification (focusing on nitrogen/crop-livestock management and digital agriculture); small holder farmers; and dietary change. We selected multi-functional landscapes, sustainable intensification, and dietary change following recent research that has identified specific sectors of food systems that, if prioritized, can deliver large co-benefits for climate change mitigation and adaptation, biodiversity protection, and degraded lands restoration[30,31,32]. We focus on smallholder farmers since their productivity and livelihoods are a major target of SDG2. For each of these areas, we offer suggestions for CA research that can stimulate new advances toward sustainability.

## Circular Agriculture Past to Present

The idea of minimizing harmful inputs and outputs in any production system through creating closed loops that recycle valuable end products back into a circular economy has been discussed for decades[33]. Several countries have pioneered versions of a circular economy as state policy (Germany in 1996, Japan in 2000), yet circularity in agriculture is a much older idea following the principles of 'grow, make, use, restore'[34]. Circular agricultural systems involve 1) system thinking to design closed cycles of nitrogen, phosphorus, carbon, energy and water along ecological cycles and waste treatment re-use along social value chains; 2) consideration of multiple organisms including microbes (bacteria and fungi), plants, animals, and insects as they form food webs from producers to decomposers; 3) innovations using smart design, digital technology, artificial intelligence, and big data; 4) and efficient and effective design and decision making across multiple scales throughout the entire value chain, often using life cycle assessment (LCA) on a farm, within a company or a country, or at the global scale[35,36]. CA is but one of several sets of practices that are aimed at implementing food system transitions; others include agroecology[37] and climate-smart regenerative agriculture[38]. There is considerable overlap among these collections of practices, even as they seek somewhat divergent goals.

Today, CA in various forms is being implemented around the world from small farm fields to large countries. There is a tremendous diversity of projects, for example, in Europe[39], Africa[40], Asia[41], North America[42], Australia[43], and South America[44]. China and the European Union (EU) are leading CA proponents. China has had a national strategy for a circular economy since 2013, making much progress in increasing resource use efficiencies, and the country has been implementing a national sustainable agriculture plan since 2015[45]. In 2018, the EU issued a farm-to-fork agricultural policy including a comprehensive set of CA practices, though it has yet to be approved by member nations[46].

One of the challenges of designing CA at any scale in any place is capturing the elements of complex food systems. These challenges are related to debates about whether to narrowly frame food systems as only about technological, supply-side issues (increase crop yields, close nutrient loops, re-couple crop-livestock links, etc.) to *produce more food efficiently*, or whether to include social and demand-side issues (improve smallholder livelihoods, create sustainable supply chains, promote dietary shifts, etc.) to *produce more food security*[47]. CA has a history of being technically framed; on these grounds, it has been critiqued for placing agricultural efficiency above social outcomes[48,49]. But including all elements of food systems in CA is not a win/lose proposition; using a social-ecological framework in a world where food systems are often inefficient *and* inequitable requires that the social aspects of food systems be accounted for. Certainly, the international discussion about food system goals is no longer confined to maximizing productivity, recapturing wastes, and lowering environmental costs; it now includes optimizing outcomes across the full range of environmental and social concerns in complex systems of production and consumption[50,51].

## Contributions of CA to Sustainable Food Systems Transformation

### *Building Multifunctional Landscapes*

Given the impacts of agriculture on natural ecosystems, it is clear that food systems transitions must include eliminating new cropland expansion into natural ecosystems while increasing on-farm protection of biodiversity, ecological functions and ecosystem services[11]. The latter can be accomplished through creating multifunctional landscapes on lands where crops are grown, thereby increasing biodiversity and ecosystem services values[52]. A host of practices are already being employed on farms to do this including: diversifying vegetation on field edges; incorporating agroforestry into fields; protecting semi-natural patches of vegetation in and around farms; creating ravine and riparian buffers; managing to increase pollinators; enhancing soil biodiversity; and more[53,54,55]. Understanding how much of the area of agricultural lands should be managed for biodiversity and ecosystem services is evolving. Currently, few countries have any minimum area requirements for conservation of natural habitats within working lands, though there is some research that shows protecting as little as 5% of within-field natural habitat yields benefits[56]. New work suggests a minimum goal of 20%, though the authors recognize that some places may need more or less land area protected[57].

In addition to these practices, innovative CA projects are moving to increase connectivity across watersheds and regional landscapes to support plant and animal dispersal[58,59]. Restoration of both on-farm and surrounding degraded lands is another practice that can link working lands with protected areas[60]. Connecting farms with larger landscapes requires a commitment from CA workers to gather science-based evidence about landscape links from field locations where they work and then sharing it with other actors at multiple scales. This is beginning to occur in China, where agricultural lands are being incorporated into spatial planning for the national system of Ecological Conservation Red Line areas[61]. At the global scale, linking food system and biodiversity goals will be especially important in 2021 since the UN Convention on Biological Diversity is convening, and the draft Global Biodiversity Framework that will set policy out to 2030 as yet contains no specific strategy for agricultural lands[62].

Given the tremendous diversity of food systems from smallholder to large corporate farms, there is much room for CA to make contributions to learning about best practices to integrate agricultural lands into multifunctional landscapes. A general strategy of testing mixes of the practices mentioned here depends on the establishment of multiple pilot projects, monitoring research results to help define what works and what does not work at scale, and identifying costs and trade-offs to optimize implementation. Three critical actions can help support successful implementation. The first is working with local farmers to discover and implement place-specific, field-level practices that have co-benefits for crop production and biodiversity[63]. The second is developing regional landscape-scale spatial planning that can explore connecting food systems with biodiversity, ecosystem services, climate, and other outcomes[64]. The third action lies with looking for opportunities to convey research outcomes to local and regional/national decision makers. These links can serve to build support for project outcomes with institutions and decision makers, and may spark initiatives that support new multifunctional landscape policies.

### *Promoting Sustainable Intensification*

Sustainable intensification, where agricultural outputs are increased while environmental impacts are reduced, is an essential component of transforming food systems[47]. There is much overlap here with CA. Sustainable intensification has focused on reducing external inputs (fertilizers, pesticides,) and decreasing environmental impacts in service of growing more food on less land. CA has emphasized closing nutrient loops and creative recycling of wastes. Both approaches begin at the field level and share a broad mix of technical practices; we focus here on two: nitrogen/crop-livestock management, and digital agriculture.

Nitrogen cycles on most agricultural lands are open, highly inefficient, and unsustainable due to the overuse of synthetic fertilizers, poor animal waste management, and the decoupling of animal/crop production loops[65]. Together, these inefficient practices have resulted in dramatic increases of various forms of nitrogen pollution in air, water, and soils[13,66,67]. Growing global livestock production resulting from increasing demand for consumption of animal products, especially meat and dairy, accounts for the vast majority of these pollutants, and there are large global disparities in all forms of nitrogen pollution between regions, countries, and subnational areas[68]. For example, fertilizer application rates in China are four times greater than in the EU, while application rates in Africa are minimal[69].

Yet the economic and social value of livestock production add complexity to finding solutions for better nitrogen management. Globally, 34% of all farm market value comes from animal products[70]. Some one billion people, mostly local smallholders often living on lands less suitable for growing crops, depend on stock for their nutrition, livelihoods, and many cultural values[71].

Ongoing research is helping to identify what places and practices must be prioritized so that CA and sustainable intensification solutions for livestock production can be better targeted and implemented. The general use of LCA is widely advocated[72,73]. Many studies also recommend particular focus on three areas: local fertilizer use efficiencies, changes in animal feed production, and manure management[66,74,75].

Numerous changes in fertilizer use efficiency are being pursued within CA. These include reducing urea-based fertilizer application rates, deep placement of fertilizers, and changes in crop straw use[76]. Much innovative work is being done with improving animal feeds including using a variety of new supplements in animal foods (food wastes, tannin-rich plants, fungi, algae, insect proteins)[77,78,79]. For improved manure management, there is active experimentation using anaerobic digesters, biogas production, membrane filtration systems, worm composting, algal cultivation, and fungal digestion[77,80,81,82].

Efforts to reconnect crop-livestock loops are focused on getting animal wastes back onto fields to replace synthetic fertilizers[83,84]. In addition, researchers are pursuing innovations using algal and fungal-based waste treatments[77]. Zhang and colleagues[85] in China have gone farther than many researchers by looking at county-level nitrogen management practices to discover and showcase where the most efficient management is being done. This kind of fine-scale research provides a model that other countries can pursue to optimize livestock management.

Nitrogen inefficiencies are not limited to agricultural practices; they occur across food systems from fertilizer production and processing to retail and trade[86]. Further, global trade in animal feedstocks (soy and corn) and meat allows importing countries to avoid the embodied LCA costs of nitrogen pollution. Embodied costs also extend to ground water depletion[87], ecosystems services[88], and carbon emissions[89]. We know of no country accounting for embodied flows in their agricultural policy or national food systems planning; this is an area where CA research using LCA and other modelling at the global scale can make important contributions.

At all scales, for nitrogen management to meet the sustainability standards of safe planetary boundaries, major transformation of conventional practices will be needed. These include more mainstream use of cost/benefit and trade-off analyses across national agricultural sectors and international trade, redesign of research programs, local extension services, agricultural credit and insurance systems, and food safety regulations[90,91]. It is also clear that increasing supply-side efficiencies without also addressing demand-side dietary change (and food loss and waste) will not solve nitrogen cycle problems[92]. The expectation is that the positive co-benefits from reduced water and air pollution and greenhouse gas emissions along with increases in benefits to public health and food security will drive increasing nitrogen cycle efficiencies throughout food systems.

### *Supporting Digital Agriculture*

Innovative use of digital technologies is expanding across food systems at all scales, providing producers with more targeted information and tools to assist with growing crops efficiently and linking them into supply chains[93,94]. Digital agriculture refers to the integrated use of digital and geospatial information technologies to assess, manage, and monitor conditions in the field so that optimal agricultural outcomes may occur. Mehrabi[95] outlines three key areas: data generation (for example, mobile devices, drones, field sensors, satellites), data processing and predictive analytics (big data, machine learning), and human–computer interactions (ways to blend voice, text and images to improve understanding and communication of results). These technologies are assisting farmers to optimize amounts, timing, and placement of fertilizers, nutrients, and water, while also enabling better monitoring and communication of environmental conditions in fields and across landscapes. Digital technologies can also help to create supply-side links to financial services for farmers and foster demand-side environmental traceability along supply chains.

Digital agriculture is evolving, but it is not a panacea to solve food system problems. While digital methodologies have been hailed as a breakthrough to provide smallholders with useful data and market links primarily through mobile phones, such use remains limited. Only 24−37% of global smallholders are connected to the Internet, and there are wide country and regional disparities in access and use[95]. In less wealthy countries, there are technological barriers due to poor internet infrastructure, data access costs, and private sector control of software and security[96]. Social barriers include disparities in adoption readiness, concerns about data ownership, and unequal gender access; these issues highlight the fact that adoption of digital agriculture has political as well as technological sides. Even where digital agriculture methods are in relative wide use, research has yet to determine their many tradeoffs[97], and economic and environmental costs/benefits[98]. CA researchers can make contributions here by using LCA studies that analyze trade-offs that extend beyond individual farms/farmers throughout supply chains to determine the comparative costs and benefits of using smart farming tools.

Overall, the future is bright for the continued expansion of multiple sustainable intensification practices. Farmers working on 9% of global agricultural lands are already implementing at least one sustainable intensification measure[47]. CA researchers can focus on how to speed up adoption of the broad range of sustainable intensification practices, especially in regions where farmer needs are great and progress has been slow.

### *Working with Smallholders*

Smallholder farmers are important actors in the transition toward sustainable food systems; they are the focus of SDG2 with its goal of doubling smallholder productivity and income by 2030. Of all farms in the world, about 83% are less than 2 h in size[99]. These farms provide 50% of global food calories and over 70% of food calories to people living in Latin America, sub-Sahara Africa, and South and East Asia[100]. At the same time, smallholders are often poor and subject to food insecurity.

Despite relatively limited research, we do know something about what smallholder farmers need to be better served in sustainable food systems. These include enhancing extension services while respecting local agricultural knowledge, building farmer cooperatives, offering education and training, securing market access, and increasing targeted forms of private sector and government support[28]. With a focus on meeting SDG2, CA researchers and practitioners can play important roles by working with smallholders to experiment with, understand, and implement these actions.

Extension services need to scale up provision of: forward-looking information about crop varieties suitable to regional changing climates[101]; methods for smallholders to re-couple crop/livestock links, including managing crop biomass[69]; and assistance with producing crops (legumes, nuts, etc.) that can replace animal products as dietary shifts occur[32]. Respect for farmers' local knowledge must be part of enhanced extension services given that smallholders have not often been consulted about their needs[102].

Farmer cooperatives and other forms of self-organized groups have been shown to support collective action around growing new crops, and gaining access to markets[103]. Co-ops often build mutual trust among farmers which is often necessary to support innovative behavior during times of change in food systems. Creating more co-ops, however, does not automatically lead to better outcomes for smallholders; group efforts often show a positive effect on farmer income and a mixed influence on crop yields and crop quality[104]. Working with farmer co-ops can help CA researchers to better evaluate costs and benefits of this form of social organization and how it may contribute to greater on-farm efficiencies and off-farm market links.

Two large studies of smallholder needs found that education and training provide important ingredients for making progress in food system transitions[101,28]. These actions can be integrated into extension services and cooperatives with particular attention paid to women, who make up about 50% of the rural agriculture labor force[105]. Women are commonly overlooked by local officials and academic researchers, but recent work is beginning to change this[106]. Chanana and colleagues[105] use a multi-factor model that maps locations where female farmers are most vulnerable to climate change and food insecurity so that decisions about where to provide services can be prioritized. This model can be adopted by CA researchers and other investigators to provide details that are specific to local research sites.

CA researchers are beginning to work to establish better links between smallholders and new markets for their products. This work often begins on a farm assisting a smallholder to connect with nearby markets (often urban consumers) to purchase her new, sustainably-grown product[107]. But it does not end there. Supply chains with their multi-faceted environmental and social footprints often extend beyond local and regional levels since one-third of all food is globally traded and crosses two or more international boundaries[70]. For globally important products like soy and beef, the embedded impacts of production and consumption have serious environmental consequences; for example, the greenhouse gas emissions footprint of beef exported to the EU from Brazil comes close to cancelling out all EU carbon mitigation goals[108]. Food systems policy research suggests building transparent and traceable supply chains from smallholder farms to global networks using digital means to close loops in tracking environmental and social costs and benefits[109,110]. This work faces complex challenges across multiple sectors of tele-coupled food systems[29]. For CA researchers working with smallholders, a critical decision is deciding how far up supply chains and away from small farm study sites one should go to account for these impacts[111,112]. Eco-certifications, improved product labelling, and LCA are tools to help do this, but transformative change in global food systems will eventually require reevaluation of national and international supply chains.

To better address the needs of smallholders far removed from global trade, local and national governments have roles to play in three main areas—infrastructure, incentives, and financial support. For infrastructure, governments should prioritize provision of irrigation for the 37% of smallholders in water-stressed regions around the globe who likely lack any means to irrigate their fields[113]. Digital network connections for smallholders and facilities for food storage and transport to reduce post-harvest food losses (and bolster farmer profits) are two additional areas where more government attention is needed. Creating positive incentives that influence smallholder behavior is another area where governments can act. These range from relatively straightforward actions like providing greater access to credit and crop insurance[107] to revising regulations for digital access and data privacy[114]. More challenging changes are the need to address long-standing land tenure problems that confer high levels of risk to farmers and reduce agricultural innovation[115].

### *Encouraging Dietary Change*

Dietary shifts toward more nutritious, plant-based foods will also be challenging as we learn how to construct a more sustainable food system. In fact, of all strategies out to 2050, plant-based diets (56% reduction) and diets following improved nutrition guidelines (29% reduction) yield the largest modelled decreases in greenhouse gas emissions from global food systems[18,116]. This means that animal products, especially meats, must play a reduced role in many human diets going forward. This is a demand-side area of food systems analysis that has been so far been little addressed by CA researchers.

Dietary shifts away from animal foods at the speed and scale that appear to be required will be difficult to encourage. Though animal products are the single largest source of greenhouse gas emissions from food systems, global production and consumption of these products are rising[5]. And there are pronounced dietary differences between countries that must be accounted for in crafting strategies to encourage shifts away from animal foods. For example, beef consumption in the US has declined almost 36% since the 1970s, but overall consumption of all meats remains very high[23]. In China, per capita meat consumption is much less than in many countries, but it is steadily rising[117].

There are multiple strategies that are essential to promoting global dietary transformative change. The question is, if dietary change is a priority, then what do we know that would facilitate the rapid adoption of new ways of eating? Given the diversity of global diets, there is no single answer to this question; dietary shifts must be attuned to every country and cultural context. However, scientific information does not much influence peoples' decision making when it comes to what they choose to eat; taste, tradition, and values about foods are more important. The main drivers of dietary change are social norms among peer groups and individuals' beliefs that what they choose to eat can contribute to group dietary shifts[118]. Lack of knowledge about the environmental impacts of food choices is widespread. Even in a relatively well-educated country such as the US, only 43% of people know about the climate impacts of eating meat[119]. This suggests that government-led programs that employ relatively strong dietary incentives will likely be needed[120]. Past government efforts to spur national dietary shifts have occurred in several countries over spans of 2–4 decades, however, most of these programs only focused on supply-side growth in crop yield and income from products with scant attention to overall food systems sustainability[121].

The Lancet Commissions' work[3] has established a global model to encourage transitions toward healthy eating. Yet, less than half of all countries have established national dietary guidelines[122], and costs of dietary change for poor people in less wealthy nations may be prohibitive without some form of subsidy[123]. An important knowledge gap that CA researchers could address here is evaluation of what cost-effective, protein-rich crops might help to replace animal products as the transition toward consuming less meat and dairy proceeds. Other steps would be for countries to solidify national dietary standards followed by efforts to reach international consensus on global guidelines and monitoring to track progress. These actions will certainly demand some form of international cooperative mechanism; it is here that trade-offs between food systems and climate, biodiversity, public health, and sustainable development goals may lead to co-benefits that compel action.

## CONCLUSION

At the beginning of this paper, we observed that humans have little historical experience with intentionally designing food systems much beyond local levels. The task humanity faces today is considerably greater; from tiny subsistence farms in sub-Sahara Africa to the more than US100 billion dollars of international trade in beef, corn, and soy, food systems require a 'major shift in mindsets'[2]; engagement with 'a massive scientific challenge'[124]; and 'radical and coordinated action'[125].

How may we accomplish these things? There is some general work that describes how social transformations unfold over 10−30 years[126,127], and reviewing the history of progress on meeting international goals for climate mitigation and biodiversity protection confirms that 2−3 decades (or more) are likely required. Studies at national[75] and global scales[32] suggest that significant progress can be made in food system transitions by 2030 and out to 2050, but none of this research comes close to projecting net zero greenhouse gas emissions from food systems. Given these timelines and projections, it is imperative that CA and all food system researchers be more cognizant of how their work addresses implementation of transformative actions as described in this paper. To encourage such efforts, we offer four observations.

First, food system researchers can benefit from what has already been discovered about how societal transformations are shaped and stimulated[128,129]. Are there actions that may accelerate change in food systems in a preferred direction? Research suggests that societal transitions may be encouraged by: supporting transdisciplinary knowledge co-production so that the science, social issues, and the politics of change are equally addressed[130,131]; identifying and then working with actors, institutions, and decision makers who are willing to support innovative projects[132]; setting strategic priorities for action since resources (funding, workers) will likely be insufficient to accomplish every task[133]; and experimenting with multiple pilot projects to learn what works best before scaling up initiatives[134]. These actions, by themselves, may not yield much momentum for change; however, used in combination, they may spark shifts that lead to deeper transformations. Researchers investigating climate change and energy transitions are already using these lessons to design projects and recommend implementation measures; CA researchers may also benefit from experimenting with these methods.

Second, it is important to emphasize how the employment of innovative tools can stimulate food systems transitions. These tools include: More frequent use of LCA to help define cost/benefits of CA projects; incorporating the full range of food system actors and institutions into CA analyses so that trade-offs throughout the system are routinely revealed; and greater use of multi-actor, multi-sector spatial assessments that build links between land, water, food, and social systems[97]. If sufficient use of these tools can be sustained across multiple sectors of a countries' food system, then the scientific basis for national planning may be strengthened. Science-based national planning may, in turn, contribute key ingredients to the negotiation of a platform for international food systems cooperation.

Third, on the matter of governance, general lessons from transformative change research along with specific observations from food systems analysts show that transitions are often slowed down by established institutions and decision-makers[135,136,137,138]. This makes sense since, by definition, CA and other movements toward food systems sustainability offer alternatives to the existing norms, policies, and power relationships of conventional, linear agriculture. Conventional agriculture actors often believe that the price of food systems transformation is prohibitive due to redistribution of cost and benefits throughout social-ecological systems[4,139]. Despite these challenges, there are methods that CA scientists and practitioners can wield to more directly address the governance aspects of food systems. One way is for CA workers to strategically use the tools and techniques outlined in this paper while continuing to ask fundamental questions: 'what does full cost accounting reveal about barriers and bridges to the true price of affecting change in food systems here?'; 'how can we work collectively with local people, government, and other actors in this place to design and implement sustainable foods solutions?'; 'who are the specific decision makers that could use my research to promote change and how do I best communicate with them?' These practical questions demand active solutions to sort out the inevitable tradeoffs that are found throughout all food systems.

Finally, it is important to remember that food systems evolve through peoples' everyday behavior where seeds of change are planted that accumulate and are amplified over time. These incremental, 'small wins'[140], 'small stories of closing loops'[141], and 'bright seeds'[142] range from a farmer adopting a climate-smart crop, to a county-level decision maker funding more extension services, to a food systems researcher incorporating ecosystem services, food systems, and urban land-use into an improved, spatially-explicit model that can better serve government planners. CA researchers do not have to foment a revolution; however, they do have to think more strategically about which steps have a better chance than others to initiate and sustain food systems transformations.

The Anthropocene will continue to offer many challenges and opportunities to effect transformative change in food, climate, and biodiversity protection so that human endeavors stay within safe planetary boundaries. In 2021, there will be additional opportunities to support secure food systems including the UN Food Systems Summit (https://www.un.org/en/food-systems-summit); the Nutrition for Growth Summit (https://nutritionforgrowth.org/events/); the Convention on Biodiversity Conference of the Parties 15 (https://www.cbd.int/convention/); and the United Nations Framework Convention on Climate Change Conference of the Parties 26 (https://www.ukcop26.org/). The time for planting transformative seeds of change is now.

## MATERIALS AND METHODS

The field of sustainable agriculture is vast; there are 685,000 hits to the subject on Google Scholar since 2016, and over 12,000 papers referenced in Scopus (as of 12/21/20). For this review paper, we did not attempt to thoroughly summarize this literature; instead, we selectively searched for papers within this extensive field that focused on circular agriculture; multifunctional landscapes; sustainable intensification (including nitrogen management in agriculture, crop/livestock management, and digital agriculture); smallholder farmers; and global and national-level dietary change. We emphasized work published since 2015 (reflecting the timeline of implementation of the SDGs), and scoping reviews and other syntheses of the above portions of the sustainable agricultural literature that offered results extending beyond a specific farm field setting. We filtered our search to highlight transdisciplinary processes and cross-links to multiple areas of food systems that suggested innovative areas of research. In all, we reviewed abstracts from 409 papers which led to the reading of 210 papers of which 142 are cited in this review.

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## Conflict of interest

The authors declare that they have no conflict of interest.

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