Circular and networked bioeconomies for Net-Zero food production

Citation for published version:
Tait, J, Raybould, A, Hoyos Flight, M & McGoohan, A 2023, 'Circular and networked bioeconomies for Net-Zero food production: There is nothing magic about circles', *Circular Economy and Sustainability*. https://doi.org/10.1007/s43615-022-00247-w

Digital Object Identifier (DOI):
10.1007/s43615-022-00247-w

Published In:
Circular Economy and Sustainability

Circular Economy and Sustainability
https://doi.org/10.1007/s43615-022-00247-w

OPINION PAPER

Circular and Networked Bioeconomies for Net-Zero Food Production: There is Nothing Magic About Circles

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Received: 9 June 2022 / Accepted: 15 December 2022

Abstract

Future food production will need to deliver a healthy diet to a growing world population whilst also contributing to policy objectives such as achieving Net Zero emissions and addressing biodiversity loss. This article looks at circular economy solutions to this challenge, comparing McArthur Foundation and other approaches to both the circular *material* economy (e.g. focusing on steel, plastics, aluminium, and cement) and the circular *bio*economy (operating in sectors that include agriculture, food production and industrial biotechnology). A case study based on salmon farming in Scotland considers the roles of innovation from a range of technology sectors in contributing to these objectives. The concept of circularity, and the closed-loop thinking that it encourages, could attract attention towards less optimal production options just because they can be accommodated within a circular model. A 'networked bioeconomy' model, guided by cascading principles and fast-tracked using innovative technologies, may be more powerful than one based on rigid closed-loop circularity, in enabling policy makers and producers to understand how they can best contribute both to the conservation of biodiversity and to mitigating climate change.

Keywords Bioeconomy · Circular economy · Innovation · Technology · Aquaculture · Sustainability

Background

Globally, food production accounts for 26% of greenhouse gas (GHG) emissions, distributed across land use (24%), crop production (27%), livestock and fisheries (31%), and the supply chain (18%) [1]. A report from the UK Department for Environment Food and Rural Affairs estimates that in the UK, GHG emissions from agriculture for 2019 were

Unfortunately Alan Raybould died unexpectedly in October 2022.

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Published online: 21 January 2023

46.3 Mt CO_2e (carbon dioxide equivalents), down from 53.1 Mt CO_2e in 1990, making up 10% of the UK's total GHG emissions and 47% of total methane emissions [2], mainly from ruminant animal production.

An important thrust of UK climate change policies [3] is promoting changes in the protein component of human diets from red meat to sources with lower associated GHG emissions, such as fish and chicken, as well as encouraging vegetarian and vegan options. This is also a feature of EU food policies for health and the environment, along with legislative reform, and funding of circular opportunities in the wider bioeconomy [4, 5]. Under the UK scenario, by 2050, UK agriculture is expected to account for 25% of the remaining GHG emissions [6]. This high proportion attributed to agriculture is due to the more radical reductions in emissions expected from other sectors of the economy, such as heating and transport. However, beyond these changes in consumer dietary behaviour, innovative technologies that are currently being developed could play a major role in further reducing food production's contributions to climate change, particularly if they are part of an integrated value chain approach.

Future food production will need to meet national and international biodiversity and climate change policy objectives, such as Net Zero [7] and the UN Sustainable Development Goals [8]. Circular economy solutions, enabled by innovation from various technology sectors, and regulatory adaptation [9], will be needed to support these transitions in the UK and the EU [10–13], and are increasingly regarded as intrinsic elements in the overall sustainability picture [14, 15].

Understanding the mismatches and potential synergies between the circular *material* economy [16] (focusing, for example, on steel, plastics, aluminium, and cement) and the circular *bio*economy [17] (operating in sectors that include agriculture, food production and industrial biotechnology) will help to identify new opportunities to optimise circularity in food production systems. Here we explore how circular economy principles can be applied to fish farming and argue that rather than an over-rigid emphasis on closed-loop circularity, establishing a network of value chains, covering both the material and the bioeconomy, may be more effective in achieving Net Zero policy goals. We also make the case that, from a sustainable development point of view, it is important to ensure that policy and technology initiatives designed to meet Net Zero targets do not have negative impacts on biodiversity and vice versa. The focus should be on initiatives that contribute positively to both Net Zero and biodiversity protection.

Circularity in the Bioeconomy and the Material Economy

Tan and Lamers [18] discuss two categories of circular economy definition: those based on the MacArthur Foundation models and 'the rest', emphasising the dominance of the MacArthur Foundation in circular economy thinking. Across the board, the circular economy is described as moving from a 'take, make, dispose' linear economy to one that puts an emphasis on making things last, keeping products in high-value use for as long as possible, reusing and repairing products, and recycling materials back into the value chain at the end of the product's life [19, 20]. These criteria work well as a foundation for conceptualising and implementing a circular material economy but they can prove problematic in a bioeconomy context for sectors such as food production.

Business Models and Value Chains

The MacArthur Foundation models envisage a common value chain for both material- and bio-based circular economies (Fig. 1) [19], from parts manufacture, to product manufacture, to service provision. While this may be a sufficiently accurate representation of a material economy, it is not a good description of most bioeconomy value chains. For example, food production may go through several stages, involving different company business models and transformations of the bio-material, rather than consciously manufacturing separate parts that are then assembled to make a product. Also, in the context of Net Zero and climate change, the bioeconomy focuses on carbon itself as an intrinsic component of products, considering the replacement of fossil fuels in production processes, using low-carbon energy inputs, sustainable supply chains, and new technologies that transform bio-resources to higher value bio-based products [18]. Capture and release of carbon as an integral component of the product, during intermediate stages of production and the final consumption process, require a more 'open' approach to the design of a circular bioeconomy than for a material economy. The intrinsic biodegradability and renewability of biological materials add a further layer of complexity and create a different range of opportunities for circular bioeconomy design.

The MacArthur models do distinguish between the material and the bioeconomy in the fate of the end products (Fig. 1) [19]. Material goods are generally not consumed in use, so maintaining their life for as long as possible is a valid objective and recycling materials at

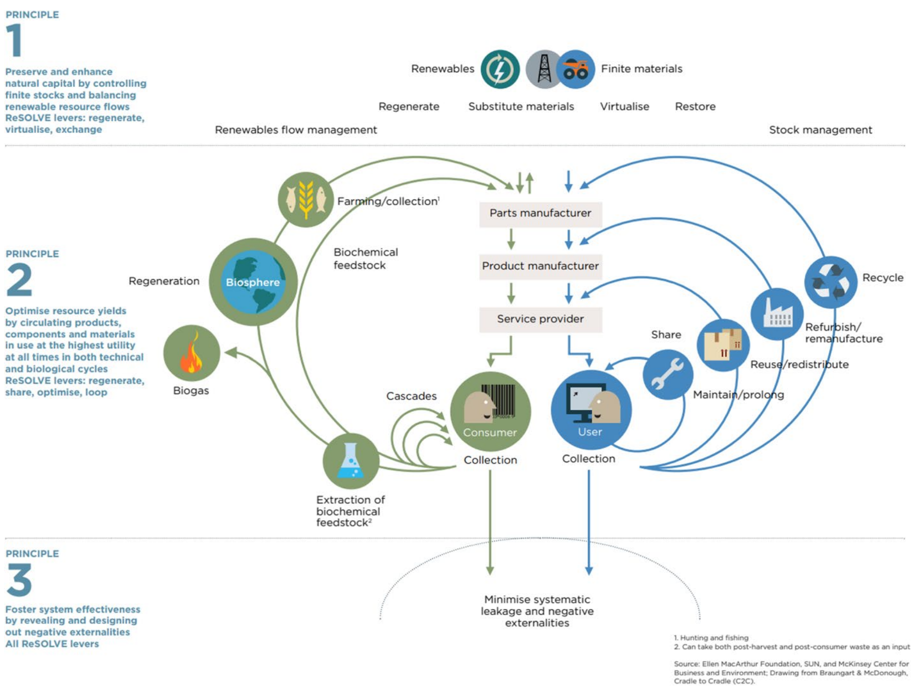

Fig. 1 Butterfly Diagram. Source: Ellen MacArthur Foundation www.ellenmacarthurfoundation.org, SUN and McKinsey Center for Business and Environment. Drawing from Braungart & McDonough, Cradle to Cradle (C2C), CC BY-NC 4.0 [https://www.macfound.org/creative-commons]

the end of life is a viable option. For food production, consumption is the expected fate of the product and sustainability would be best served by minimising the amount of bio-material that is not consumed in use (i.e. food waste), hence minimising the amount of material available for re-use or recycling at the end of the value chain. (This article does not tackle the very important, but also very difficult, question of the use of human sewage.)

Closed Loops and Cascades

Closed loops are a key element of the MacArthur approach with recommendations to "… keep components and materials in closed loops and prioritise inner loops" (Fig. 1) [19]. The international standard ISO 14044 [21] describes closed loops as the recovery and recycling of materials for their original purpose without change to their inherent properties, as epitomised in a material circular economy; in open loops, the recovered materials have different inherent properties and are used for purposes other than the original, as is more likely to be the case in a bioeconomy. However, even in the material economy, there are sometimes good reasons to favour open-loop recycling [22].

The related cascading principle also implies the use and re-use of by-products that are produced at various stages of a product's development and proposes criteria for choosing among different recycling opportunities. Material that is not incorporated within the commercial end-product should be captured at each stage in the value chain and diverted into a cascade of consecutive processes, maintaining it in higher-value states, from the point of view of carbon sequestration, for as long as possible. In a circular bioeconomy, from a Net Zero perspective, conversion of carbon-containing by-products, such as carbon dioxide, into semi-permanent products such as bio-plastics [22] or building materials [23], removing the by-products, long term, from the circular economy value chain, would be the highest value use. Options such as recycling into food production systems would be of intermediate value and fuel use or waste disposal would be the least desirable option [24]. Campbell-Johnston et al. [25] have noted that little research has been done on how to operationalise the cascading principle and integrate it with other circular economy principles and yet, as we claim here, it may be more important for cutting GHG emissions in the bioeconomy than the principle of circularity itself.

The Role of Innovative Technologies

The MacArthur Foundation report on a circular economy vision for Europe acknowledges the importance of technological innovation in delivering a circular material economy, with a 7% increase in impact above current projections in gross domestic product (GDP) by 2030 and 12% by 2050. It states, "The key reason for the difference is that this report assumes a substantially higher pace of technology change in the big product and resource sectors … compared to what has been observed in the past …" [19]. However, the role of genetic technologies in European agriculture and food production has been controversial, and the MacArthur Foundation report on circularity in European food systems does not mention a role for technological innovation, proposing only socioeconomic solutions—regenerative farming practices, changing diets towards alternative, vegetarian and vegan protein sources, and reducing food waste [26]. There has been a pervasive anti-technology discourse on sustainable farming systems in Europe over the past 30 years [27, 28], with few added insights or prescriptions arising from circular economy thinking and other technology and policy developments, reinforced in the EU Farm to Fork Strategy [29]. This anti-technology, particularly anti-biotechnology, perspective on food production systems could prevent the EU from meeting the nutritional needs of its population while also delivering on Net Zero and biodiversity objectives, particularly when one considers the adverse effects on biodiversity and GHG emissions resulting from producing food for import into the EU to make up for shortfalls in EU food production [30, 31].

Achieving these outcomes in the necessary timescale will require a creative and discriminating approach to technological innovation (including biotechnologies, robotics, big data, and artificial intelligence), along with new business models and value chains, a more nuanced understanding of the nature of circularity in food production and different supporting policies and regulations [32], compared to the status quo and to a material-based circular economy.

The following case study on fish farming in Scotland [33] was undertaken to explore how best to apply circular economy insights to food-related bioeconomy value chains.

Putting a Circular Food Bioeconomy into Practice in Aquaculture: Case Study on Salmon Farming in Scotland

The ideas and concepts discussed in this paper were partly stimulated by a research case study on Scottish aquaculture and its contribution to Net Zero and biodiversity policies [33]. This provided an opportunity to explore some of our evolving thinking on circular economy concepts and their implementation.

Global increases in fish consumption, partly caused by the growing global population, and climate change policies encouraging changes in diets, are expected to lead to significant increases in the demand for fish protein. However, most wild fish stocks are either over-fished (approx. 30%) or fished at their maximum sustainable yield (60%) [34]. Thus, although many forms of capture fishery production have been shown to be low in GHG emissions, and sometimes are lower than aquaculture production, the required increase in production will need to come from farmed species [35].

The Scottish aquaculture sector has ambitious plans to double the economic value of production by 2030 [36]. It is currently the third largest salmon producer in the world after Norway and Chile and salmon is the UK's third largest food export by value [37]. The sector is already becoming more sustainable by reducing its impact on marine biodiversity and contributing to Net Zero climate change policies [33, 36], and this case study explored how technology options could improve its future performance in these areas. However, some options that could lower GHG emissions could have damaging impacts on marine or land biodiversity and our analysis took these factors into account. A detailed description of the technologies, their stage of development and uptake, and their potential future impact is included in the aquaculture case study report [33].

The value chain relationships that emerged in this case study (Fig. 2) are more complex than those implied in the McArthur models, indicating the need for linked, not necessarily circular, value chains and company business models involving inputs and outputs that cannot be envisaged as part of a *circular aquaculture* bioeconomy. In this figure, the central circular economy value chain encapsulates elements that could be incorporated within a McArthur-style circular bioeconomy. As described below, there are also inputs (bottom left corner) and outputs (top right corner) that involve other value chains beyond aquaculture and businesses engaged in wider networked economies. In some cases, these will be potentially circular economies in sectors other than aquaculture. In other cases, they will be 'open loop' opportunities, delivering significant

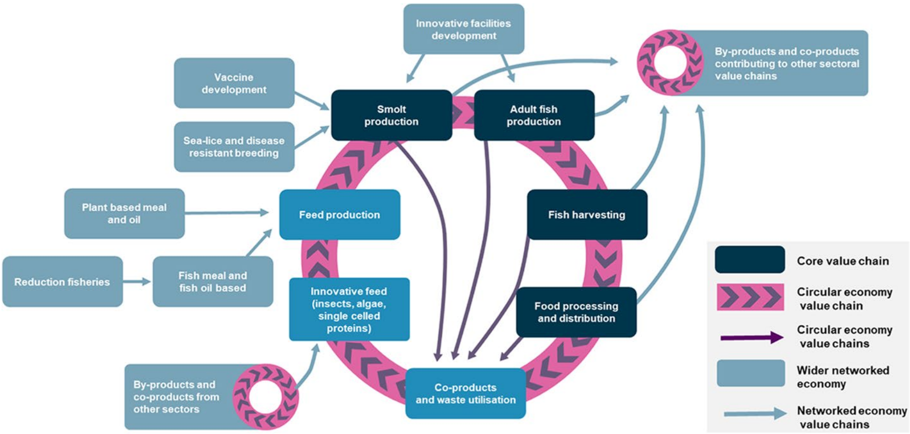

Fig. 2 The circular economy value network and the role of innovative technologies for Scottish salmon farming

benefits for important health and environment-related policies, but not necessarily aspiring to deliver circularity.

Technology Options

The following innovative technologies contribute, at various points along the production value chain, to achieving the aims of government policies on Net Zero, the circular bioeconomy, zero waste, and protecting marine biodiversity.

Novel Animal Feed Sources

Fish feed, required for salmon production, can account for over 90% of fish-to-farm-gate GHG emissions [38] and is the most expensive component of aquaculture production. Previous reliance on fishmeal and omega-3 oils from wild capture fisheries has placed significant pressure on wild fish populations with impacts on marine biodiversity. Among other factors such as concern over security of supply, this has resulted in a shift to greater reliance on plant-based ingredients, most commonly soya meal that now comprises around 50% of feed [38]. This has reduced the pressure on marine ecosystems, but it has increased GHG emissions and shifted some of the biodiversity impact to land ecosystems such as the Amazon rainforest and the Cerrado savannah in Brazil [39]. Potentially more sustainable feed options are now being developed using single-celled protein from micro-organisms and black soldier fly or yellow mealworm larvae, developed using by-products from unrelated industry sectors, including inputs such as methane, carbon dioxide, hydrogen, and non-domestic food waste. These future feed ingredients could be produced closer to the point of use than current soya products, saving on transport costs and emissions, and making supply chains shorter and more reliable.

New Production Systems (Innovative Facilities)

There are new, material economy rather than bio-based, systems that are designed to increase production capacity, reduce environmental impacts, meet planning-related challenges, and increase overall control of aquaculture production systems [33]. They include the following:

- Off-shore high energy systems, defined as production in exposed sites usually more than 2 km from shore [40], have benefits to fish health, reduced environmental impact from waste, and greater efficiency from larger scale production. They also have technical, staff risk-related and energy-use problems that are still to be resolved. Depending on the source of power used to support them, GHG emissions from off-shore systems can be higher than those from conventional production systems closer in-shore.
- Closed containment systems located in sheltered in-shore or off-shore waters are mainly used as nurseries or for on-growing salmon smolts so that they can be transferred to a marine environment at a larger size. They can reduce energy consumption by 75%, increase the feed conversion ratio and reduce fish mortalities.
- Recirculating aquaculture systems on land, mainly used as hatcheries and nurseries, have been in use for many years, but improvements in production capacity, energy systems, waste recovery, and water cleaning will contribute to meeting climate change and biodiversity targets.

Food Processing and Waste Utilisation

Waste elimination and by-product utilisation at the food processing stage of salmon food production are core elements of a circular economy approach.

- By-products are already incorporated into co-products in related sectors, or recycled within a salmon farming circular economy; for example, using viscera to make fishmeal and fish oil, fish heads to make salmon oil, and trimmings for domestic food use.
- Relevant to a material circular economy, re-usable bulk bins for domestic supply chains, replacing polystyrene boxes, have led to an estimated saving so far of 4.1 Kt CO_2-e [41], with potential to increase if the innovation is taken up by more companies.
- Development of biodegradable packaging based on chitin, a by-product from crustacean production, is being supported by the UK supermarket Waitrose.
- Where the production system allows capture of un-eaten feed and faeces, a major focus of concern for the Scottish Government, they can be used as biofuel or fertiliser. Fish blood is also used for these purposes.
- Where mortality occurs, dead fish are being processed in one location by anaerobic digestion to produce biofuel to replace diesel oil for fishery service vehicles. However, innovative technologies can also reduce fish mortality, reducing the viability of this kind of recycling option (see below).
- Fish processing by-products can be used for terrestrial livestock feed, pet food and pharmaceuticals, further reducing their reliance on fishmeal and fish oil from wild capture fisheries.

Animal Breeding, Health and Welfare

Fish health and welfare issues are seen as a top priority by the aquaculture sector [42] and many innovations are already well established across the industry. New innovations under development include vaccines against pathogens and treatments for sea lice infestations (thermal treatments, mechanical removal, biological control using 'cleaner fish', and underwater lasers). The new production systems discussed above could also deliver benefits in sea lice control, as could breeding for sea lice resistance in salmon [43].

Conclusions from the Aquaculture Case Study

This case study was undertaken partly to test our emerging critique of circular economy concepts as they are applied to food-related bioeconomies, drawing on, but not necessarily dominated by, circular economy thinking. The main conclusion was the need for policies to speed up development of innovative sources of aqua-feed with the potential to improve both biodiversity and climate change-related impacts of fish farming [44]. Current feed products will be based for some time on a combination of wild-caught fish and soya meal with both climate change and biodiversity impacts and there is a need to speed up production of alternative, more sustainable feed sources. This case study also noted that future expansion in protein production from marine sources could be even more sustainable if it focused on lower-trophic fish and filter feeders, rather than carnivores [33].

We observed that a more complex networked, rather than circular, bioeconomy approach would be a better foundation for future strategic planning and policy making, optimising the opportunities for resource conservation and re-use across a broad range of value chains, rather than focusing primarily on closed-loop circularity.

As illustrated in Fig. 2, the core fish farming, protein production value chain is becoming part of a circular economy, both bio and material, based on innovative technologies, that could contribute to and benefit from links with other value chains, creating what could more accurately be called a 'networked economy' rather than a circular economy. This analysis is based on a methodological approach to which the authors have contributed [45] that builds on systemic analysis of innovation processes in companies and the ecosystem factors that influence translation of products to market readiness. We are proposing that these considerations are a useful addition to the already extensive body of literature on circular economy analysis [e.g. 17, 18, 19, 24, 25, 26, 46].

Re-thinking Our Approach to Circularity: a Network of Open- and Closed-Loop Opportunities

The Innogen Institute's approach to innovation management includes optimising company interactions along the entire value chain in addition to considering individual company business models, and analysing the impacts on product development of the innovation ecosystem (intellectual property, regulation/governance systems, and stakeholder perspectives and interactions) [45]. As demonstrated in the case study, this approach is proving useful in evaluating the role of circular economy thinking in delivering innovations that are economically viable, contribute to climate change mitigation, and are beneficial to health and the environment.

In a protein production circular economy where the food end-product will largely be consumed, some of the criteria applied to evaluation of a circular material economy are not relevant. However, as shown in Fig. 2, there are opportunities at several points in this circular bioeconomy to reintroduce by-products into the core value chain, to smolt and adult fish production, and to harvesting and processing. This MacArthur-style closed-loop circular bioeconomy model uses cascading to maintain by-products in an intermediate-value state, mainly other food uses (animal feed or fertiliser), with some low-value biofuel use. Figure 2 also demonstrates opportunities beyond the closed-loop system, in a wider network of open-loop bio- or material economies, where these by-products could contribute to other food and non-food value chains, potentially cascading to higher-value uses not available in a strictly circular bioeconomy; for example fish scales and skin can be made into alternatives to leather [46].

The key message is that recycling opportunities within a closed-loop circular bioeconomy may be inferior to those in wider, networked, open-loop systems. The optimal cascading opportunities in food production systems may come from cascading some co-products to higher value uses in the emerging bio-material economy (manufacturing bioplastics [22] or building materials [23]) rather than retaining them in a more circular model within the food and feed bioeconomy.

As in fish farming, advances in innovative technologies will play an essential role across the bioeconomy in safe-guarding food security and quality, while also reducing GHG emissions and promoting the use of by-products. Innovative biotechnologies, such as genome editing and synthetic biology, are likely to be among the most powerful contributors to circular bioeconomy objectives and we should avoid making invalid assumptions about the incompatibility of such products with sustainable development objectives or simply defining products of these technologies as unsustainable.

The circular economy and the associated concepts of closed-loop and open-loop recycling along with the cascading principle are making invaluable contributions to the vital, climate change-driven transformation of material economies and bioeconomies. Also, the concept of a circular economy is increasingly gaining traction among companies, policy makers, and governments, and insights and analyses such as those presented here could be counter-productive if they undermined decision makers' confidence in circular economy models.

We are making the case that an optimal approach to delivering Net Zero and biodiversity commitments may best be achieved by a circular economy approach that extends to a wider, networked system of value chains within which there are many, connected, open loop, recycling opportunities (Fig. 2). As Stegman et al. [17] point out, a circular bioeconomy is not inherently sustainable and there is a need to address potential trade-offs, by facilitating cooperation across value chains and optimising cascading pathways.

Given the complexity of interactions across this wider landscape of value chains, such an approach would help guide policy interventions and research support to areas where there is clear, preferably quantitative, evidence for expected improvements in GHG emissions. The approach should focus on the options with the biggest potential gains and those where synergy among recycling initiatives could maximise positive outcomes. Particularly in the food bioeconomy, strictly closed-loop thinking may divert attention away from superior options just because they cannot be accommodated within a narrow circular model. A more widely networked circular bioeconomy, guided by cascading principles, may be a more powerful model in enabling policy makers and producers to understand the actual and potential shape of the whole production system within which they are located, and how they can best contribute to both conserving biodiversity and mitigating climate change.

Funding The research on which this article is based was funded by an Open University QR Policy Funding grant.

Declarations

Competing Interests The authors declare no competing interests.

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