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Resilience by industrial symbiosis? A discussion on risk, opportunities and challenges for food production in the perspective of the food-energy-water nexus

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Abstract

Background: Growing population and affluence coupled with climate change puts pressure on the supply of food, water and energy. The three are interconnected, conceptualised in the food-energy-water nexus. In this article, two innovative proposals for food production based on recirculating, multiloop systems are analysed in terms of risk and resilience to illuminate how such industrial symbiotic systems might contribute to food supply resilience, within nexus constraints.

Method: The proposals encompass greenhouses using waste heat and carbon dioxide combined with recirculating aquaculture systems (RAS) with water, nutrient and energy loops between the two. The two cases are discussed in comparison with the existing major alternatives for production of the respective foodstuffs, using an inventory of global risks as a structure for the discussion. The analysis is relevant to understanding current and emerging risks posed by the unsustainable and interlinked supply of food, energy and water, particularly in the perspective of continued climate change.

Results: Based on the cases, the concept of distributed, symbiotic food production is discussed in comparison with centralization, i.e. the economies of symbiosis vs economies of scale, focusing especially on how these different economies affect risk and resilience. The discussion centres on a comparative risk analysis between food production in industrial symbiosis and conventional forms.

Conclusions: The results indicate that distributed symbiotic food production can contribute to resilience to the most threatening of the relevant risks identified and that, therefore, more in depth investigations of how symbiotic systems can contribute to resilience are merited. These, in turn, would warrant an informed discussion on food-production policy.

Keywords: Climate change, Resilience, Industrial Symbiosis, Risk, Food-energy-water nexus, Food security

Introduction

The purpose of this article is to discuss how innovative food production systems based on industrial symbioses may contribute to *resilience* in food production.

Climate change, caused by anthropogenic emissions of greenhouse gases poses a catastrophic threat to human lives, well-being and the means to sustain basic needs. It is not only a threat; already climate change, including increasingly frequent extreme weather occurrences, causes serious harm to supply chains [1]. The supply of three basic human needs of food, water and energy have become so interlinked that with current supply systems, increasing the supply of one affects the conditions for supplying the others. This is called the food-energy-water nexus [2]. Some, but not all, renewable energy forms help resolve the nexus, but despite recent expansion are considered to be decades from becoming sufficiently competitive to edge out fossil fuels [3]. The nexus challenge is not just a competition for resources

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and lack of capacity to increase output, even retaining current levels of supply is unsustainable. The dominant forms of current food production are dependent on fossil fuels and an unsustainable level of water consumption, in competition with other uses. The concept of a food-energy-water nexus has drawn attention to how development of each supply individually of the others decreases overall resource security. Furthermore, the future study and development of the sustainable supply of these needs is in need of a better understanding of risk [4].

The food-energy-water nexus is particularly troublesome because demand for all three needs is increasing, fuelled by population growth and economic growth. The increased affluence of the most populous Asian countries has increased demand for resource-heavy proteins at previously unaffordable levels. Put differently, an effect of the food-energy-water nexus is that western-style consumption levels cannot be sustainably supplied to everyone with current systems and methods [5].

Background

This article will analyse two case studies with food production based on industrial heat recycling and recirculating systems. Both cases include a greenhouse and fish farm, but other elements differ between the two. The analysis will be used to discuss whether similar initiatives could contribute to mitigating the risks to food security posed by climate change by designing nexus-sensitive production systems. Both cases are conceptual designs with financial modelling, but not yet in operation or construction. The cases are richly described in public documents, making them easily accessible for future research. Because neither of the cases has yet been fully realized, all figures are calculations and estimates, rather than measured results.

Food production systems are of particular interest because "… food production is among the largest drivers of global environmental change by contributing to climate change, biodiversity loss, freshwater use, interference with the global nitrogen and phosphorous cycles, and land-system change" [6]. Within food production, protein is of special interest, as global demand is increasing as populations become more affluent. This is causing a nexus conflict.

An estimated 16% of the world's population is dependent on fish for their primary source of nutrition. At the same time, a third of global fish stocks are fished over the limits of biological sustainability. This means there is direct food-food competition in which the more affluent populations risk taking fish from groups without other means of acquiring similar sustenance. Wild fish harvest has effectively peaked. The continued world increase in demand must be met by aquaculture. However, off-shore aquaculture is beset with a raft of environmental issues, including eutrophication caused by fish excrement, spread of disease, leakage of antibiotics to combat the diseases and the creation of antibiotic-resistant bacteria. These environmental issues limit the growth of off-shore aquaculture. Deep-water open farming is mooted as a solution but does not actually solve any of the ecological issues – rather, it dilutes them at significant expense [7, 8].

The first case, the European Spallation Source ESS, is research infrastructure: a research facility of a scale comparable to a medium-sized heavy industry plant [9]. The second case, called RePro Food, is an innovation development project sponsored by the Swedish government agency for innovation, Vinnova.[1] Vinnova demands extensive reporting in exchange for its grants. Both cases are designed for heat recycling and food production on a scale dictated by the availability of the waste streams on which they are based. The data in both cases comes from the design phase of facilities, with a level of detail sufficient to calculate investments and returns to present to investors.

The cases are not entirely independent. Although at different locations and actors, the locations are only 50 km apart, there was communication between the actors in the cases, and some key people moved between the projects. Due to their geographic proximity it follows that the proposed facilities would operate in similar market conditions, the most relevant markets being those of energy, tomatoes and fish. Important market characteristics are that the cases were developed in the one of the world's best functioning markets for electricity, where hourly supply and demand forms the electricity price, with well-established trading of forward contracts providing predictability and price security. For tomatoes, competitiveness in enhanced by the transportation costs to Sweden from the European continent forming a cost threshold for foreign competition. Additionally, a preference for home grown produce provide price premium and 42% of Swedish consumers express a willingness to pay extra for sustainable food, representing a significant opportunity for premium pricing [10].

The combination of tomatoes and fish in both cases was based on nutrient recycling from a fish farm on land to a greenhouse. This arrangement allows production of protein-rich food with minimal environmental impact, by recirculating water and nutrients [11]. Particularly, the systems address the key role of phosphorous and the need to conserve phosphorous as a scarce resource and simultaneously address an overabundance in inland and coastal waters [12]. The cases encompass water recycling

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[1] See section 5.3 Availability of data and materials

from rainwater. Future water availability is another issue of the food-energy-water nexus and climate change [13].

In summary, the production of the world's food supply is a significant contributor to climate change, as well as an unsustainable consumer of water. Simultaneously, climate change is a major threat to food production. The two case studies were selected for their apparent potential to contribute both to sustainable food production and to mitigate risk induced by climate change. The purpose of the analysis in this paper is to structure a discussion of that potential, and that of similar efforts globally. The discussion is structured around the three questions:

1. What current and emerging risks in the agro-food sector can be identified to which the cases are relevant?
2. To what extent could the systems presented in the cases contribute to resilience in food supply in relation to identified risks, seen in their respective markets?
3. To what extent could the systems or processes presented in the cases contribute to resilience in food supply in relation to identified risks, seen globally?

Method

The case studies are examples of *industrial symbiosis* [14]. Industrial symbiosis denotes a relationship between unrelated but co-located businesses that share resources for mutual profit viewed in the perspective of *industrial ecology* [15]. Industrial ecology is a methodology that views industry as flows of materials and energy and the development of material and energy efficiency in business as analogous to processes of natural selection in nature. The literature suggests that efforts in industrial symbiosis may be particularly conducive to innovation [16].

We use the term resilience to denote the ability to withstand adverse change and the concept of risk as the product of an adverse impact and the probability of its occurrence. A related concept pair is security-vulnerability, wherein a "vulnerability model" in the literature includes exposure, sensitivity, adaptive capacity and general risk as subordinate concepts [17]. The cases are chosen due to their potential benefit from a food-energy-water nexus point of view. To ensure a holistic systems-thinking approach, the comparison benefits of a broader risk framework. As our point of departure for a categorisation of important global risks, we have chosen the Global Risk Report from the World Economic Forum [18, 19]. An alternative framework for risk assessment might be the concept of Planetary Boundaries [20]. This framework has been used as a basis for a proposal for a system of management and accounting [21]. The expansion from accounting indicators to risk assessment would be a small one. However, the focus only on environmental, "planetary" boundaries may ignore substantial social and economic issues and thereby introduce an unwanted limitation. The WEF risk report has an implied perspective of economic risk (e.g. to insurers), and is not without bias. Nonetheless, the publisher is a recognised international, independent actor. The WEF risk report was therefore chosen as the most broadly accepted framework to discuss risk.

The twelve above-average risks measured by impact listed in the Global Risk Report are as follows[2]:

1. Weapons of mass destruction
2. Extreme weather events
3. Natural disasters
4. Failure of climate change mitigation and adaption
5. Water crisis
6. Cyberattacks
7. Large-scale involuntary migration
8. Food crisis
9. Spread of infectious diseases
10. Man-made environmental disasters
11. Interstate conflict
12. Critical information infrastructure breakdown

Among lower-impact risks are several related to financials, including fiscal crisis, un- or underemployment, asset bubbles in a major economy, energy price shocks and failure of financial mechanisms or institutions. Another group is risks pertains to government, including failure of national governance, failure of regional or global governance and state collapse or crisis.

As a basis to discuss risk profiles, we use a comparative analysis, comparing the proposed production facilities to their most likely alternatives, identified in the market analysis of the respective business cases. A comparative analysis is used to enable conclusions to be drawn, without the benefit of quantitative data. Both the greenhouse and the fish farm have two distinct types of competing production. The risk analysis therefore comprised of four different comparisons:

A. Distributed symbiotic greenhouses compared to import from large-scale greenhouses in the Netherlands
B. Distributed symbiotic greenhouses compared to import from open-air farming in Spain

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[2] The list presented is from the 2018 Global Risk Report, as this was the latest when the research was conducted. The order is somewhat changed in the 2019 assessment. Because the risk categories are grouped for the purpose of the discussion in this paper, the changes between the 2018 and 2019 risk reports do not substantially affect the analysis.

C. Distributed symbiotic fish farms compared to wild fish capture
D. Distributed symbiotic fish farms compared to off-shore fish farms

Limitations

Early work on industrial symbiosis has indicated that distributed production systems such as the symbiotic production presented in the cases might form the basis for distributed economies [22, 23]. The distributed symbiotic system might therefore offer opportunity for more local supply than current production or full-scale stand-alone facilities. Actually achieving local supply would require innovation and change in the supporting logistics systems, something not described in the cases. This possibility is therefore left out of the scope of the analysis.

The starting point in WEF Global Risk Report provides a broad and independent source of risk factors to consider of which many are directly or indirectly relatable to food production. However, the list is not fully comprehensive and taking such a broad view of risks inevitably sacrifices depth, so that significant risks and issues specific to the agro-food sector may not be included in the top global risks, and therefore not part of the basis of the comparison in this paper.

Case studies

First case: European spallation source ESS

The first case study is the European Spallation Source ESS, a research facility being built in Lund, Sweden comparable in physical size and scope of energy transformation to a medium-sized heavy industry plant. ESS is a neutron source that will provide, when complete and at full power in 2025, the world's brightest neutron beams, enabling scientists to peer inside materials with spatial resolution in nanometres and time resolution in nanoseconds. Spallation is the process of freeing neutrons from atomic nuclei. At ESS, the spallation will be powered by the world's most powerful linear accelerator, about 500 m long. To achieve this world-leading performance, the design of ESS demanded substantial innovation. At the same time, the demands for scientific quality place extreme requirements for reliability, monitoring and replicability [9].

To decide where in Europe to locate ESS, a competition was arranged, in which Sweden and Denmark participated as "ESS Scandinavia" with Lund as the proposed site. In addition to marketing the university town of Lund and promising substantial cash contributions, ESS Scandinavia committed to building "the world's first sustainable research facility". The claim to sustainability rested on an "energy concept" called "Responsible, Renewable, Recyclable", with ambitious targets for improved energy efficiency, sourcing with renewable energy and heat recycling [24]. The ESS energy concept represented a significant innovation [25].

The energy systems of ESS are complex. The range of cooling needs spans from the superconducting linear accelerator at under two Kelvin to the nuclear processes in the target, the spallation, hot enough to instantly vaporise molecules of the target material. The extreme values were captured in specialised systems, so that the site-wide cooling systems had three levels, one for chilled water, one for warm water such as would be conventionally supplied by cooling towers or a body of water, and one for hot water. The hot-water cooling loop was an innovation to make direct use of the local district heating system that supplied heat to the buildings of Lund. Recycling to district heating required a temperature of 80 °C and returned a temperature of around 50°. A significant part of the energy effort at ESS was devoted to finding equipment that could be cooled, or could be redesigned to be cooled, at the hot range. Because the heat recycling commitment prohibited the use of cooling towers and the district heating system was the only available heat sink, all lower temperatures necessitated the use of heat pumps. The physics of the Carnot efficiency dictate that the efficiency for a heat pump falls with greater temperature differences. The result was a dilemma. Recycling the waste heat would cost substantial electricity use, conflicting with the first priority of energy efficiency [26].

The conundrum could be solved by finding a lower-temperature heat sink than the district heating system. To this end, ESS held an Open Call for uses of waste heat. This produced a great range of suggestions for use of waste heat, most of which required a temperature difference of around 80 °C or more, in order to achieve acceptable efficiency. Since the challenge was to use lower temperature heat, and no cold temperature source was available, all suggestions based on heat engines had to be discarded. What was left made clear that temperatures as low as 40° can be used for space heating, although the systems to distribute the heat will be more expensive than for higher temperatures. Heat at 60° can be used without significantly increased investment compared to conventional solutions [26].

Heat at around 40° could also be used for low-temperature drying, such as of biomass for biofuel, to drive digestion or fermentation processes, or for water treatment, all uses that would contribute to various forms of renewable energy production or ecological improvement, but sadly no commercial opportunities were identified. Commercial viability was a necessity, as ESS did not have investment budget for such systems to use its waste heat. Therefore, the systems needed to be sufficiently commercially attractive to attract the necessary investment. In the climate surrounding ESS, inexpensive space heating was found to make greenhouse farming of tomatoes profitable. Greenhouse farming in Sweden has a comparative disadvantage in the cost of heating, compared to facilities on the continent. If that disadvantage was offset by inexpensive waste heat, comparative advantages such as ample access to clean water and a competitive electricity price would make the facility competitive and attract investment [26].

The open call also resulted in proposals for use of heat at even lower temperatures. Two of these were explored further in the case. One of these was an on-land, recirculating fish farm. The species of fish proposed were such that temperatures of just under 20° would be used. In many climates, this might as well be a cooling temperature as a heating temperature, but the ambient conditions were such that holding 20° would require heat for almost all the year in average years. The ESS operation schedule also called for the main shut-down period for maintenance to be in the summer months and cooling needs would be much lower during maintenance. In any case, the cooling benefit of the fish farm would be small compared to the greenhouse. Instead the main contribution from the fish farm was to expand the business case and add to the sustainability of the whole by creating an additional loop for recirculation, this one carrying nutrients from fish excrements to the greenhouse to be used as fertiliser. This improves the sustainability of the greenhouse by replacing commercial fertiliser, which is energy-intensive in production, with a renewable resource [27].

The second low-temperature heat sink proposed was a system for ground heat for open-air farming. This system would involve installing a system of plastic pipes under an entire field and result in the annual yield from the field doubling by lengthening the growing season enough for two harvests. Unfortunately, preliminary calculations indicated that the installations would be expensive compared to the modest value of the types of crops enabled by the production form. The only way the system would be profitable was if ESS would pay for the cooling. Cooling to the same temperature as the farmland would deliver, around 12 °C, would entail a cost, either for buying and operating chillers, or as a purchased service. The problem that arose was that the open call was part of a process to attempt to demonstrate a value of waste heat that could be sold from ESS. ESS was and is a public entity, constrained by rules for public purchasing. There are no corresponding rules governing the sale of waste heat. The effect was that the option to use an open call and other instruments to stimulate innovation were not available to the ESS Energy Division without going through a public procurement process.

Second case: RePro food[3]

RePro Food was an innovation and development project initiated by Findus, a frozen food company. Findus is the leading company within the frozen fish category in Sweden and has a long tradition of innovation as well as introduction of previously unknown species or concepts, such as the Marine Stewardship Council (MSC) certification standard, to the Swedish market. The project was stage two out of a possible three stages of challenge-driven innovation process. The first stage had been a market investigation and was used to estimate target prices and volumes for tomatoes and various fish species. The third stage would be to move from development to investment. The project called for a greenhouse and fish farm to be developed at Findus' production site in the town of Bjuv [28].

Other than Findus, the collaborating partners were Veolia Sweden, an energy service provider that supplied the Bjuv site with heating and cooling, Royal Pride Sweden, the Swedish subsidiary of a leading tomato grower in the Netherlands, Vegafish, a small enterprise for prawn and fish farming, the municipality of Bjuv, with an interest in job creation locally, SLU, the Swedish University for Agricultural Sciences, Söderåsens Biogas, a local producer of biogas from farm waste, and WA3RM, a brand-new company formed by former employees of the ESS Energy Division [28].

In contrast with the ESS project that was driven from the need to recycle heat and therefore to demonstrate that a business case existed, RePro Food was driven by an interest to invest and establish greenhouse growing in Sweden based on import of technology and know-how from the Netherlands and therefore resulted in detailed investment calculations and a full model of profit and loss, balances and cash flows of the business over 20 years, to be presented to investors. This material is now in the public domain. The fish farming was not based on an established business and therefore is described in considerably less detail, but nonetheless modelled for profitability [29, 30] .

The project called for the construction of a 15-ha greenhouse and a fish farm for 1500 t of fish per year. A greenhouse of 15 ha would be Sweden's largest. The market investigations in stage 1 of the project had indicated a market capacity for greenhouses in Sweden of 900 ha, although this indication may have underestimated the production per ha and was later revised downward in the project. In any case, only 13% of tomatoes consumed in Sweden at the time, were domestically produced. The project estimated that 50% home production was achievable, particularly since the greenhouse design envisaged the inclusion of grow-lights, for year-round production.

The size of the fish farm in an integrated system is limited by the size of the greenhouse, as this dictates the

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[3] Reports from the project are available at www.reprofood.com. Public documents from the municipal detailed plan are available (in Swedish) at www.bjuv.se under the site name Selleberga 17:1.

capacity to accept the nutrient effluent of the fish and researchers at SLU had calculated that 100 t of fish would fertilise 1 hectare of greenhouse tomatoes. A fish farm for 1500 t represented a step-change in magnitude compared to existing experimental facilities, with capacities ranging from single digits in tonnes to around 60. In contrast, two identified commercial fish farms in planning simultaneously with RePro Food intended 6000 and 10,000 t respectively.

Statistics for annual average rainfall on the greenhouse showed that in normal conditions, the rainwater falling on site, if collected and stored, would be sufficient for the needs of the greenhouse. A system to collect and store rainwater was in any case a requirement for a building permit, to prevent flooding. The integrated greenhouse-fish farm design envisioned rainwater collected from the rainfall would go first to the fish farm (after treatment) and then on to greenhouse drip irrigation system, via the control system for fertiliser dosage, which would balance nutrients as necessary.

With world demand for fish growing while supply is limited, the market in the long term would not seem to be a limiting factor, but investment calculations necessitated more exact data. Such data for Findus' target markets had been acquired in the stage 1 pre-study and formed the basis for a project decision to design the fish farm for farming 50% pike-perch and 50% rainbow trout. Both species were in high demand and therefore commanded an attractive price.

The heat recycling from Findus food processing factory presented multiple challenges for the energy engineers at Veolia and for the designers of the greenhouse for Royal Pride Sweden. Firstly, the temperatures were very low creating a challenge to conserve temperature quality and combine flows to raise supply temperatures and to create a system to use the lowest possible temperature to heat the greenhouse. Secondly, the waste water stream holding the most energy contained food residues, posing a challenge to retrieve the heat from the effluent to heating water without clogging the heat exchanger moving the heat between them. This was solved by Veolia, whose engineers identified a technology with a continually reversing heat exchanger. Thirdly, heat capacity was not constant and the demand from the greenhouse would vary seasonally and with daily weather. A possible solution that was explored, which could also serve as a back-up heat source, was a geothermal heating combined with drilled ground storage. Such systems had been put in place in the vicinity and could be studied. Unfortunately, Bjuv is an old mining town, where lignite was mined underground but close to the surface. Investigations revealed that the greenhouse site was crisscrossed underneath with mining tunnels, making drilled storage impossible and even dangerous, due to risk of collapsing tunnels [31, 32].

In a surprise development, while the project was ongoing, Findus announced the closure of the plant, removing the source of waste heat. The parties together initiated a search for other alternatives for the same site. The efforts were ultimately futile, and the project at Bjuv mothballed, but the process of evaluating other heat sources necessitated the development of appraisal methods applicable to other projects. Beyond assessing heat quality and quantity, also variations over time, the investigations revealed the importance of differentiating between energy and power (energy per unit time). A heat supply might be sufficient to cover annual energy needs, but inadequate to cover peak demand (the power need) or be of varying power in supply. Calculations confirmed that a heat capacity that covered base need of the food production facilities could be economical to develop, even if it necessitated a top-up for a few days a year. In such a case, the running cost of the top-up was of small importance, if the investment cost was low. As a result, an oil boiler was selected for this need. With such a limited planned running-time, the sustainability impact of the use of oil was deemed to be negligible. However, the project parties were aware that the use of fossil fuels, even as back-up, might render the production ineligible for eco-labelling. In the case, eco-labelling of the tomatoes was not a goal.

A parallel project also initiated by Findus investigated the possibility to use waste from Findus' production of frozen peas as an ingredient in fish fodder. The pea plant parts are relatively protein-rich plant matter. Initial experiments showed promise in that plant-based material was fed to Tilapia (a vegetable-eating fish species), thereby suggesting the possibility of another recycling loop in the system, of food processing waste to the fish farm. For predator species, two notable methods for development of fish fodder production facilitated with waste heat were mooted in the same period as the project, one with fly larvae and one using yeast. In either case, production could be based on farm and food waste substrates, or even slaughterhouse waste and human waste in sewage. Some combinations struggle with the "yuck-factor". Beyond such subjective perceptions, legal- and hygiene issues were identified, the most challenging were connected to legislation passed to prevent the spread of mad-cow disease, or BSE, Bovine Spongiform Encephalopathy. The case study business case reveals that fish fodder is the dominant variable cost for fish farming and therefore the most attractive for management to improve profitability. Furthermore, because the RePro Food project planned for farming predator species, availability of fish fodder not based on wild fish capture was fundamental to the long-term sustainability profile.

The detailed budgets developed for the greenhouse farming in RePro Food revealed that the cost of carbon dioxide (CO_2) for use in the greenhouse, although less than the cost of heating, was substantial. CO_2 is conventionally supplied in liquid form by truck, at significant expense. Moreover, the delivery requires major investment in a receiving, storage and expansion station capable of transferring the CO_2 at the high pressure and low temperature required for liquid storage, and to heat and expand the CO_2 for use. Greenhouses in the Netherlands are predominantly heated with natural gas, which is by many considered to burn cleanly enough to use the CO_2 produced directly in the greenhouse, at minimal expense. The business case demonstrated that the cost of CO_2 significantly adversely affected the competitiveness of greenhouse developments in Sweden compared to imports. For that reason, it was an important conclusion from RePro Food that future projects should include recycling of CO_2 from industry, in addition to heat.

Continued technical development and deployment

We, the authors of this article, from our positions as two of the partners of RePro Food can report that although the project in itself is completed, the work continues within and between several project partners. Although the results this work are not yet reported, the publicly available grant applications for the case and a possible continuation offer a glimpse into current issues and developments in relation to the project, as a starting point for the discussion. The first such development worth mentioning is that after the abortive project in Bjuv, several projects making use of the RePro Food material are in various stages of development at other sites in various places in Sweden using waste heat from the metal industry and from pulp and paper, the two sectors that dominate heavy industry in Sweden.

A second development is the inclusion of efforts to achieve CO_2-recycling from heavy industry in accordance with the results of RePro Food. The heavy industry investigated emits CO_2 from various processes. Depending on the specifics of each process, the concentration of CO_2 in flue gases varies greatly, as does the composition of other gases emitted with the CO_2. Four categories of technical challenges have been encountered. The first issue is corrosion caused by gases containing substances such as sulphur that combine with water vapour and condense into acids that harm the equipment for capture of heat and CO_2. The second is the blockage of distribution pipes caused by condensation of water vapour in the flue gas. The third issue is damage to plant growth caused by pollutants potentially harmful to plants. The fourth issue is worker health and safety in the greenhouse potentially affected by gases harmful to humans. All these issues could be avoided by extracting the CO_2 from the flue gases. Processes to achieve this have been in focus for development for Carbon Capture and Storage, CCS, a sustainability effort in energy transformation. However, preliminary investigations indicate that these processes are not necessarily appropriate or economical to transfer directly to the problem of capturing CO_2 from industrial flue gases for use in greenhouses.

The third ongoing development is a rethink on fish species to farm. As noted in the case description, the choice of species to farm was driven primarily by market demand and competition (in fact, the upstream supply chain and other factors also entered into the decision). The problem with the selected species, and other species considered, was that all are predators. The available fish fodder for these was primarily based on wild capture of species less attractive for human consumption. Because each tonne of these species produced in a fish farm requires more than a tonne of fodder, the net result could be increase of wild fish capture. The development of fodder from land-based proteins, such as described in the case, would alleviate this problem, but for that development to gain momentum would require a sufficient market for fodder, creating a chicken-and-egg situation as neither the fish farms nor the fodder production could start without the other if the fish farming was to be sustainable.

An alternative to inventing new types of fodder would be to introduce new, vegetable-eating species to consumers, species that can eat a vegetable feed. This would require a far greater marketing investment and also lose the price premium commanded for known and popular species. Instead, a possible price premium could derive from the sustainability of the product. A production base of vegetable-eating fish would have the added value of creating a source for fish fodder for predator fish, using discarded parts of the vegetable-eating fish.

The grant applications promise substantial job creation as an outcome of the projects. Explorative investigations referenced in the applications revealed that in the general case, for the envisioned project locations, attracting the required human resources for comparatively low-skill and low-pay jobs harvesting tomatoes would require recruitment from groups not active in the job market, explicitly including recently arrived immigrants. Because the greenhouse design included growlights for year-round production, the jobs would be full-year rather than seasonal. The business cases reported in RePro Food demonstrate that the cost of labour is an important factor for competitiveness [29].

The RePro Food Investment Memorandum describes a project with 15 ha of greenhouse compared to an estimated need of 900 ha, with similar limitations to fish. The limited production capacity in the case study system is an effect of limited supply of waste resources at each location. Thus, the economy of the resource efficient symbiotic systems needs to outweigh the economies of scale of the stand-alone system to be competitive. The business case calculations indicated that this was the case, but the data for comparison for the fish production was limited. In order to secure access to know-how, purchasing power, bargaining power for sales and systems for operations, the projects envisaged a roll-out based on a franchise model or similar structure, wherein the facilities distributed to places where waste resources are available form a structure, thus forming a d*istributed symbiotic system*.

Heat recycling and quality

The cases hinge on heat recycling. Heat is conducive to growth in organisms, within a range specific to each organism, but typically organisms do not fare well at temperatures higher than their specific range. Uses of waste heat are temperature sensitive, as are the industrial processes which supply the waste heat through their cooling systems. Because of these sensitivities, thermodynamics will enter into the analysis.[4]

The starting point of both cases was to make use of waste heat, the temperatures of which were too low compared to ambient conditions to drive a heat engine, as illustrated in the formula for the Carnot efficiency. The waste heat was therefore only useful for heating, either of a space or of a liquid flow. Because heat is difficult to transport (but relatively easy to store), a further constraint was that the heat must be used locally.

Discussion

Resilience characteristics of the distributed symbiotic systems

As a foundation to discuss the resilience of the envisioned distributed symbiotic systems in answer to the research questions, we begin by summarising and characterising the risk profiles of the systems as perceived in the case studies. The pivotal contribution of the case studies is to detail how economies of symbiosis could outweigh economies of scale.

The ESS case included a proposal for using waste heat for augmented open-air farming and demonstrated that this development would require an interest to pay for cooling. The cooling temperatures received from such a heating and cooling loop were estimated in the range of 10–12 °C, depending on the ambient ground water temperature and details of system design. The value of this service hinges on the Carnot efficiency. Each step lower in temperature increases the efficiency of chillers as well as doing part of the work. For example, without the ground heat addition, the systems in the case studies would return a temperature of around 20°, depending on the fish species, for the heat needed for the fish farm (less than for the greenhouse). If, for example, a cooling temperature of 5° is required, and an added ground heating/cooling loop would lower the temperature to 12.5°, then half of the cooling work has been done by the additional loop. In addition, the chiller (a type of heat pump, which is a heat engine in reverse) required to cool from 12.5° to 5° would operate at a greater Carnot efficiency. Less energy would be required to cool the remaining half of the temperature gap, per unit of heat cooled. The case is interesting, as industrial modernisation entails greater electrification and lower cooling temperatures, meaning that industry in the future could gain efficiency with access to colder sources of cooling. An interesting detail is that the ESS case contains two data centres in addition to the particle accelerator and its neutron-producing target. The digital economy has caused the proliferation of data centres requiring[5] low cooling temperatures, greatly increasing demand for low-temperature cooling.

The case study business cases demonstrate profitability for the symbiotic systems of tomato greenhouses and fish farming, indicating that such systems are capable of absorbing the cost of the recirculation systems that enable symbiosis. For example, the return on equity on the infrastructure investments for RePro Food given as 8.5% and the operating margin for the greenhouse was well over 50%. Once these systems are established, new elements could be added to the symbiosis at a lower cost, if doing so was in the interest of the established units, for example by improving their business case or the sustainability profile. Production of fish fodder, whether from yeast or larvae, from a waste substrate, using waste heat could improve both profitability and sustainability. The future innovation and development possibilities for a new food chain for proteins represent a substantial

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[4] The theoretical *Carnot efficiency* of a heat engine plays an important role. The Carnot efficiency calculates the maximum theoretical efficiency for a heat engine. Heat engines encompass a wide variety of energy transformations in which heat energy is converted to mechanical energy, including motor engines, combustion-based power plants and heat pumps. Refrigerators and air conditioners are heat pumps in reverse, and also governed by the Carnot efficiency. The formula for Carnot efficiency states that the maximum theoretical efficiency is given by one minus the quotient between the high temperature and the low temperature of the engine ($\eta_{max} = 1 - T_c/T_h$). Temperature is measured from absolute zero (in the unit Kelvin), meaning that for a low temperature based on ambient air or typical room temperature, a hot temperature of around 600 K or 327 °C is required to achieve 50% theoretical efficiency, because the ambient cooling temperature is likely to be around 300 K. The Carnot efficiency is a theoretical maximum, meaning that actual achieved efficiencies are lower. The Carnot efficiency plays a pivotal role in the design of systems based on heat recycling.

[5] In the workshop series Energy for Sustainable Science initiated by ESS, CERN and European national laboratories, it has been mooted that like particle accelerators, data centers may not need to be cooled at such low temperatures.

sustainability opportunity. Conversely, lack of an existing sustainable supply chain represents a substantial risk. Similarly, the recycling of CO_2 emissions from industry is an attractive opportunity for the greenhouse grower, as the cost for carbon dioxide is of similar importance as for energy, but the lack of a developed technology for small scale capture and distribution represents a substantial risk [30].

In summary, the risk profile of the distributed symbiotic systems is characterised by, firstly, resource efficiency, the symbiotic sharing of resources representing a step-change in resource efficiency, including improving the efficiency of the host industry. Secondly, the proposed systems are semi-closed systems with multiple-loop recirculation, implying a high degree of control and a low degree of exposure to outside conditions, but a new risk exposure from the interdependency between systems in the symbiosis. Thirdly, the intensive, comparatively high-tech farming systems represent substantial investment, and thereby investment risk. Fourthly, the innovation environment described in the cases represents risk.

Risk categories

Returning to the three questions posed in the introduction to structure the discussion, the first question was "What current and emerging risks in the agro-food sector can be identified to which the cases are relevant?"

Starting with the risk categorisation from the World Economic Forum described in the Introduction section of this article, we find that the cases have little relevance to the greatest impact risk, *weapons of mass destruction*, nor do the cases provide basis for comparisons of resilience on the sixth risk, *cyberattacks*, nor the twelfth, *critical information infrastructure breakdown*. These risks are therefore left out of the scope of the discussion. For the sake of brevity, and because the similarity of impacts on the cases, the second, third and fourth categories, *extreme weather events*, *natural disasters* and *failure of climate change mitigation and adaption* are considered together, and *water crisis* and *food crisis* are considered together with other issues of resource scarcity in a *nexus* category, including such issues as limitations in production capacity and scarcity of resources, including farmland, and also absorbing the lower-level risk category *energy price shocks.* In this category, also issues of self-sufficiency and food fraud are considered. The seventh category, *large-scale involuntary migration*, is included only as an issue of *employment*, thereby also capturing some lower-level risks reported by the World Economic Forum such as *un- or underemployment*. In this category, we also discuss safe working conditions.

The use of antibiotics in today's open systems for offshore fish farms illustrate a direct relevance of the ninth category, spread of infectious diseases, which for brevity is renamed *disease* [8, 27]. Antibiotics leaking to the environment might also be conceived to be an environmental issue. In a quantitative analysis, characteristics affecting multiple categories would be counted to each category, to the extent they contributed. However, in this high-level discussion, such repetition would merely duplicate discussion points and is therefore avoided by discussion each characteristic in the most relevant category only.

Category ten, *Man-made environmental disasters* is renamed *Environment* to clearly include issues such as pollutants in uncontrolled production environments affecting produce, e.g. collapse of wild fish stocks, eutrophication and microplastics in fish. Interstate conflict, category eleven, is replaced with a catchall category for risks related to *government*, thus including significant risks identified in the cases, such as interventions, protectionism, subsidies and trade-wars.

An aggregate category entitled *economics* captures investment risk including the lower-impact risks *fiscal crisis*, *asset bubbles in a major economy*, and *failure of financial mechanism or institution*. The *economics* category also encompasses the risks identified in the cases connected to industrial churn, the rise and fall of industries and its effects on societies and resources. Lastly, a new risk category is introduced named *supply chain*, in order to capture the operational risks in the cases, including the supplies to production facilities of plants/smolt and fertiliser. The supply chain category also captures risks connected to transportation, including waste, costs, and environmental effects. Also, the supply of know-how and technology to the production system is considered as part of the supply chain. A summary of the risk categories used is given in Table 1.

There are surely other risks, and alternative categorisations. The list presented does include risks external to the case projects, but the focus of the case material is on investment risk, risks that effect profitability of the case projects. This would include risks to competitors, which may be a positive outcome for a project, for instance by raising prices for the produce, but a risk from a broader social perspective. Nonetheless, we surmise that the risks presented in the case materials represent the most important risks to the projects in the cases and thus a relevant perspective of analysis.

Comparisons of risk and resilience

The cases at this stage provide insufficient basis to quantify probabilities or effects, allowing only a qualitative analysis at this time. The second research question in the introduction opens the analysis; it was "To what extent do the systems presented in the cases contribute to resilience in food supply in relation to identified risks,

Table 1 List of risk categories

No.	Name	Contents
i	Extreme weather	Extreme weather events, natural disasters and failure of climate change mitigation and adaption
ii	Employment	Employment effects of large-scale involuntary migration, un- and underemployment, safe working conditions
iii	Nexus	Food-energy-water nexus issues, water crisis, food crisis, limits in supply and production capacity, quality risks, energy price shock
iv	Disease	Spread of infectious diseases, use of antibiotics and the resulting creation of resistant organisms, spread of disease in fish and vegetables within production facilities and between facilities and their environment
v	Environment	Anthropogenic environmental disasters and effects of man-made pollution, including issues such as bycatch of wild fish and monoculture fields as well as over-fishing, eco-system collapse, and eutrophication
vi	Government	Interventions, protectionism, subsidies, trade-wars
vii	Economics	Investment risk e.g. leading to high interest rates, fiscal crisis, asset bubbles in a major economy, and failure of financial mechanism or institution. Also, industrial plant closures
viii	Supply chain	Supply of key inputs such as plants/smolt and fertiliser; also, know-how and technology, i.e. access to human resources and to the requisite production technology; transportation, including costs, environmental effects, losses/waste

seen in their respective markets?". To answer this, we use the comparative analysis introduced in the methods section, comparing the proposed production facilities to their competition, resulting in four different comparisons:

A. Distributed symbiotic greenhouses compared to import from large-scale greenhouses in the Netherlands
B. Distributed symbiotic greenhouses compared to import from open-air farming in Spain
C. Distributed symbiotic fish farms compared to wild fish capture
D. Distributed symbiotic fish farms compared to off-shore fish farms

Starting with the comparison between the smaller, distributed symbiotic greenhouses in the case with the larger, specialised greenhouses that currently supply imports, and proceeding in the order of the presented risk categories, the risk profiles differ as follows:

i. *Extreme weather*: The symbiotic facility may be better able to spread the risks from extreme weather within the symbiosis group, by sharing resources. Distributed production facilities would lessen the risk of all production being hit by the same extreme weather, while correspondingly increasing the probability that some production would be affected. As it happens, the facilities in the Netherlands used in the comparison are on reclaimed land below sea level and are exposed to risk connected to rising sea levels. In total, the difference in risk level is too small to be assessed with the data available.
ii. *Employment*: The distributed symbiotic systems would offer similar numbers of job opportunities (about 60) as the comparison facility, only relocating jobs. Therefore, the risk profile is similar.
iii. *Nexus*: Resource efficiency was the driving factor behind the creation of the industrial symbiotic systems in the cases, creating substantial differences in risk exposure compared to stand-alone facilities. The use of waste resources removes direct exposure to volatile energy markets and the resulting cost risk. However, significant exposure could nonetheless remain via the host industry, that might reduce production and thereby access to waste heat. On the other hand, an industry that has a small income from selling waste heat would have a competitive advantage in the event of a world energy price shock. Such mutual advantage with the symbiotic system is an example of how industrial symbiosis may create resilience.
iv. *Disease*: The RePro Food greenhouse was divided into four sections [33]. An environmental impact assessment was conducted as a part of the municipal planning process necessary for permitting [34]. The sectioning helps prevent spread of disease and pests. The geographical separation of distributed facilities may provide an additional barrier to limit spread of disease.
v. *Environment*: The symbiotic facility is designed to recycle nutrients from fish as fertiliser, creating sustainability benefits in avoiding commercial fertiliser as well as risk of eutrophication from effluents from fish farming. For the RePro Food case, 43 tons of nutrients would be recycled as fertiliser, divided into 15 tons of nitrogen compounds, two tons of phosphorous and 26 tons of potassium. Thereby, conventional risks associated with fertiliser and eutrophication may be largely avoided. On the other hand, new risks arise with the complexity of the symbiotic system so that disruption in one facility in the local symbiosis may disturb another. System design would need to be

robust for planned variations and thus likely to be robust for lesser disturbances, but back-up for full-scale failures would likely depend on conventional solutions.

vi. *Government*: Both facility types would be subject to the whims of government, but the difference between the two cannot be assessed with available data.
vii. *Economics*: The smaller facilities based on industrial symbiosis clearly have a major risk exposure to the closure of the anchor plant facility, as evidenced by the plant closure which terminated the RePro Food project.
viii. *Supply chain*: The first facilities in distributed systems, perhaps farming tomatoes and fish in regions with no such traditions, would be exposed to greater supply chain risk until capacity and know-how is built up in the distributed group. As for transportation, the domestic supply envisioned in the case would lessen risk compared to import, as well as delivering a price premium.

The comparison for each risk category is summarised in Table 2.

The next comparison is between the distributed symbiotic greenhouses and imports from open-air farming, which for the cases in Sweden would largely come from Spain, including the Canary Islands off the coast of Africa. Again proceeding in the order of the presented risk categories, the risk profiles in this comparison differ as follows:

i. *Extreme weather*: The symbiotic greenhouse would be more resilient to weather conditions than the open-air farming.
ii. *Employment*: The cases do not supply data on the job-intensity of open-air farming.
iii. *Nexus*: The same advantages as in the previous comparison are applicable. Additionally, we note that greenhouse farming is more intensive than open-air, with multiple times greater yields per area. The area for a greenhouse need not be arable land (although it does need to be flat). Indeed, in modern greenhouses the production does not use soil at all; nutrients and water are dripped onto roots in a substrate, controlled even on the level of individual plants. Greenhouse farming is therefore systemically less exposed to risks connected to the large monocultures in open-air farming.
iv. *Disease*: The greenhouse facilities would have far greater ability to control the growing environment and limit the spread of disease.
v. *Environment*: The same characteristics as in the previous comparison are applicable. Additionally, open-air systems risk leaking nutrients to their environment.
vi. *Government*: Government action is common in the agricultural sector, and changes in subsidies, taxes, regulations or conditions of trade can substantially affect competitiveness and profitability. An example of this in the cases was that the businesses cases were built on the current condition that greenhouse farming is considered an energy-intensive business and pays energy tax at the lowest rate (0,005 SEK/kWh, compared with the highest rate of 0,335 SEK/kWh), payable on the electricity use. This was the greatest risk identified in the business cases.
vii. *Economics*: Greenhouse farming is far more intensive, but also requires far more investment, meaning that sudden rises in interest rates and

Table 2 Risks in distributed symbiotic systems compared to import from full-scale greenhouses

No.	Name	Compared Resilience	Reason
i	Extreme weather	=	Small differences
ii	Employment	=	Difference of location only
iii	Nexus	+	Better resource efficiency
iv	Disease	=	Small difference because of mitigation action
v	Environment	+	Symbiotic facilities avoid eutrophication risks
vi	Government	?	Different but no basis for assessment
vii	Economics	–	Exposure to anchor industry
i.viii	Supply chain	-	Risk during roll-out before the total distributed system achieves bargaining power and know-how
		+	Domestic supply better for transportation Price premium for local produce

Legend:
+ Better resilience for distributed symbiotic systems
- Better resilience for comparison facility
= No difference assessable with case data
? Different risk profiles but not assessable with case data

other costs of financing would affect greenhouses much more.

viii. *Supply chain*: As in the previous comparison, the earliest facilities in distributed systems, perhaps farming tomatoes and fish in regions with no such traditions, may be exposed to greater supply chain risk until capacity and know-how is built up in the distributed group, but no such risk is identified in the project risk assessments. As for transportation, the case studies do indicate that the domestic supply envisioned in the case would lessen cost and risk compared to import even more than in the previous comparison, as well as delivering a price premium.

The comparison for each risk category is summarised in Table 3.

Moving to fish, and the comparison between distributed symbiotic fish farms and wild fish capture, and proceeding in the order of the presented risk categories, the risk profiles differ as follows:

i. *Extreme weather*: Events such as hurricanes can prevent fishing but are limited in time. The symbiotic fish farms could conceivably be affected by draught, if rainfall on the greenhouse and storage became insufficient and other water supply restricted. A more likely event might be disruptions in supply chains caused by extreme events, see further under category viii. The compared production forms therefore have entirely different risk exposures to extreme events, but both appear to have small probabilities of major exposure, compared to other risks.

ii. *Employment*: The fish farming facilities described in the cases offer ten full-time employment opportunities. The controlled work environment would be substantially safer than for off-shore fishing.

iii. *Nexus*: Wild catch fishing has peaked. Annual captures vary with quotas that are set based on scientific studies, but in a political process, therefore reflecting also other concerns than ecological balance. Symbiotic fish-farming is extremely resource efficient. On-land fish farming can be a major net contributor to food supply, but only if the fish farmed does not depend on wild fish capture for its fodder. If the symbiotic systems can farm fish without using fodder from fishing, then they will offer considerable resilience to nexus risks. This implies farming a herbivore species of fish. The market studies in the RePro Food case demonstrate that the most attractive species on the market are carnivores. Therefore, farming a herbivore presents a market risk. Conversely, there is an opportunity in that the waste from slaughter and fileting (about 40% of weight) would make excellent fodder for carnivore species.

iv. *Disease*: The on-land facilities would have greater ability to control their environment and limit the spread of disease and greater opportunity for treatment, but the concentration of intensive farming weakens resilience to spread of disease in the flock. As a direct result, risks connected to spread of antibiotics are unique to farming but manageable in a controlled system, offsetting the increased risk. Neither system increases spread of disease in the wild. They are therefore assessed to be equal in resilience.

v. *Environment*: Fishing has permanently decimated fish stocks in many places and caused secondary effects through bycatches and altered eco-systems.

Table 3 Risks in distributed symbiotic systems compared to import from full-scale greenhouses

No.	Name	Compared Resilience	Reason
i	Extreme weather	+	Closed or semi-closed systems more resilient
ii	Employment	?	Data not available
iii	Nexus	+	Better resource efficiency
iv	Disease	+	Closed or semi-closed systems more resilient
v	Environment	+	Symbiotic facilities avoid eutrophication risks
vi	Government	–	Risk exposure in greenhouses to energy tax
vii	Economics	–	Exposure to costs of financing and to anchor industry
i.viii	Supply chain	-	Risk during roll-out before the total distributed system achieves bargaining power
		+	Domestic supply better for transportation and can deliver a price premium

Legend:
+ Better resilience for distributed symbiotic systems
- Better resilience for comparison facility
= No difference assessable with case data
? Different risk profiles but not assessable with case data

The gradual warming of the seas affects fish stocks. Coral ecosystems may be affected by the increase in acidity resulting for higher CO_2 levels in the air. Wild fishing is exposed to the effects of eutrophication in coastal waters, harming marine ecosystems and harvests. Fish farms must release nutrients built up in the water from excrement. This requires filtration technology and a recipient, in the symbiotic systems represented by the greenhouse. Both could conceivably fail, representing a technical risk, but insignificant compared to the exposure of fishing.

vi. *Government*: Government action is common in fishing, and changes in subsidies, taxes, regulations or conditions of trade can substantially affect competitiveness and profitability. Government could markedly affect both fish farming and wild fishing and the relationship between them but assessing the comparative risk would require relevant data not present in the cases.

vii. *Economics*: The proposed farming system is more requires more investment than fishing, but has lower running-costs, meaning that sudden rises in interest rates and other costs of financing would affect the on-land facilities more, whereas fishing would be more exposed to fluctuations in fuel prices.

viii. *Supply chain*: As fishing boats must go farther for their catches, transportation becomes an increasing issue. The emerging technologies of fish farming initially represent a risk in know-how and technology compared to the well-established wild fisheries. Instead of natural ecosystems and quotas, farms rely on a supply chain for inputs, which represents a risk, especially as these are weak in the nascent industry.

The comparison for each risk category is summarised in Table 4.

Comparing the symbiotic fish farms in the cases to off-shore fish farms, reveals risk profiles heavily favouring the on-land, controlled systems in the cases:

i. *Extreme weather*: Extreme weather events can disrupt or even destroy off-shore fish farms. Thus, the symbiotic systems are more resilient.

ii. *Employment*: As a result of the greater resource efficiency, the symbiotic fish farming allows greater employee productivity than off-shore, implying greater resilience to adverse change, greater job security.

iii. *Nexus*: Symbiotic fish-farming is vastly more resource efficient, recycling nutrients instead of releasing them and causing eutrophication, as off-shore facilities must. The symbiotic systems are therefore considerably more resilient.

iv. *Disease*: The symbiotic facilities are more resilient as they would have greater ability to control their environment and limit the spread of disease and greater opportunity for treatment, without spread of antibiotics to the surrounding environment.

v. *Environment*: The open off-shore systems are dependent on their environment but pollute it with nutrients from excrement. Therefore, the symbiotic systems are more resilient.

Table 4 Risks in distributed symbiotic systems compared to wild fish capture

No.	Name	Compared Resilience	Reason
i	Extreme weather	=	Different risks but of lesser significance for both
ii	Employment	+	Better control of working environment on-shore and inside
iii	Nexus	+	Better resource efficiency
		+	Potential for substantial improvement in food supply if wild fish-based fodder is avoided
iv	Disease	=	The risks of intensive farming are offset by the manageability of semi-closed systems.
v	Environment	+	Controlled environment poses less risk.
vi	Government	?	Different but no basis for assessment
i.vii	Economics	-	Exposure to costs of financing and to anchor industry
		+	Resilient to fuel costs
i.viii	Supply chain	-	Risk during roll-out – longer time period before the sum achieves bargaining power
		+	Domestic supply better for transportation

Legend:
+ Better resilience for distributed symbiotic systems
- Better resilience for comparison facility
= No difference assessable with case data
? Different risk profiles but not assessable with case data

vi. *Government*: Because of the environmental impacts of off-shore fish farming, government actions to limit it are likely. Although the novelty of the proposed symbiotic systems may increase the likelihood of being affected by government intervention, the known risk for off-shore farming is judged to be the greater.
vii. *Economics*: On-land fish farming requires more investment, meaning that sudden rises in interest rates and other costs of financing would affect the on-land facilities much more. Additionally, symbiotic fish farms are dependent on their symbiosis partners.
viii. *Supply chain*: The supply chain for on- and off-shore is too similar to assess a difference with available data.

The comparison for each risk category is summarised in Table 5.

Taken all four together, the comparisons illustrate that the distributed symbiotic systems offer better resilience for the top five risk categories: extreme weather, employment, nexus, disease and environment. For the sixth category, government, the case data does not allow an assessment. The distributed symbiotic systems have greater risk exposure in category seven, economics, due to the high investment. Additionally, at least initially, the distributed symbiotic systems would have greater exposure in category eight, supply chain.

Generalisability

Since the cases were so close geographically, generalisability must be considered carefully. The last research question was “To what extent could the systems or processes presented in the cases contribute to resilience in food supply in relation to identified risks, seen globally?”. Once again proceeding in the order of the presented risk categories, the geographical issues identified are as follows:

i. *Extreme weather*: The case geographies have relatively little exposure to extreme weather and natural disasters. The extreme weather events planned for in the cases include high winds and torrential rain, events to which the semi-closed, controlled distributed symbiotic systems would offer greater resilience than outdoor forms of production. Risk of events such as earthquakes, tornados or hail might affect design of facilities in the symbiotic systems and represent risk exposure in other geographies.
ii. *Employment*: Although job markets differ widely, the local benefit of more, stable, and safe employment may be considered general. A general benefit occurs when the production increases total supply to meet increased world demand, so that new employment is created.
iii. *Nexus*: The recycling model underlying the symbiotic systems in the cases is designed for a cool climate. The waste heat benefiting the greenhouses in the cases did so because ambient conditions imposed a requirement for heat. In warm climates, cooling and water scarcity are greater challenges. Waste heat could be useful for these issues as well, with heat-driven cooling and water treatment, as were identified in the cases. However, the limited scope of the cases, and the vast array of differing operating environments and associated challenges prevent any general conclusions outside of cool climates. The limitation of applicability to cool climates, however, still includes a significant portion of the world’s population, potentially encompassing the north of Europe, Asia and North America.
iv. *Disease*: The symbiotic systems’ greater ability to control their environment and limit the spread of disease would seem to be general. In less developed farming systems, use of antibiotics are potentially

Table 5 Risks in distributed symbiotic systems compared to off-shore fish farms

No.	Name	Compared Resilience	Reason
i	Extreme weather	+	On-land systems less exposed to adverse weather
ii	Employment	+	Better job security and working conditions on land
iii	Nexus	+	Better resource efficiency
iv	Disease	+	Closed or semi-closed systems more resilient
v	Environment	+	Symbiotic facilities avoid polluting and the effects of pollution
vi	Government	+	Off-shore fish farming risks greater limitation by government
vii	Economics	–	Exposure to costs of financing and to anchor industry
viii	Supply chain	=	Similar risk profiles

Legend:
+ Better resilience for distributed symbiotic systems
- Better resilience for comparison facility
= No difference assessable with case data
? Different risk profiles but not assessable with case data

less well-managed, making the difference to symbiotic systems advantage even greater.

v. *Environment*: Again, the symbiotic systems' greater ability to control their environment and limit the spread of pollution would seem to be general. In less developed farming systems, use of pesticides and fertilizers are potentially less well-managed, making the difference to symbiotic system's advantage even greater.
vi. *Government*: Risks connected to government interventions are global and even less predictable in areas without the benefits of transparency and democracy or plagued by corruption. It seems clear that these are palpable risks, but the case studies investigated do not provide a basis for generalisable conclusions. This is therefore an area meriting further study.
vii. *Economics*: The greater exposure to financial markets from the greater investment in the symbiotic systems would be a global phenomenon, worse in areas with less developed financial markets.
viii. *Supply chain*: Infrastructure for transportation varies widely. In the cases, the greenhouses benefited from a small but noticeable barrier for foreign competition in the costs of transportation but otherwise the facilities would have access to excellent infrastructure. This would not necessarily be the case in other parts of the world, where food supply may suffer huge losses in regions with poor infrastructure. For places with poor infrastructure, local food production could be major benefit, but carry corresponding risks for non-local items in the supply chain. Local produce in many areas earns a price premium, as in the cases studied, but in less developed countries, imported goods instead carry a price premium reflecting a perception of higher quality or status, especially better food safety. The net effects are worthy of further study.

In summary, this brief analysis indicates that the results may be applicable in geographies characterised by cool climates, good transport infrastructure and stable government. For warm climates and areas with poor infrastructure, the benefits of distributed symbiotic systems would seem to warrant further research and development.

Concluding remarks

Despite limited quantified risk data in many risk categories, the analysis suggests that the distributed symbiotic food production systems presented in the case studies may have the potential to offer greater resilience to the relevant risks with the greatest potential impact than the four alternative systems examined, among other things offering better security of food supply and food quality with the help of controlled environments, as well as better resource efficiency. Additionally, it seems that the resilience demonstrated in the cases may be achievable in other geographies that share the conditions of cool climate, functional transport infrastructure and stable government.

On the other hand, the greater investment for the case study systems represent a risk exposure to financial markets and the level of innovation in the systems conveys technical risk. Also, the symbiotic systems have risk exposure to the anchor industry in the symbiosis. The significant environmental benefits of the symbiotic facilities may induce government support to offset the investment risks, but that assessment is outside of the scope of analysis enabled by the case study data.

As noted in the section on limitations, this high-level examination cannot explore all sector-specific risks in detail. Rather, it serves to highlight areas of potential interest for detailed, quantified examination. Potential other research areas include expanding the risk categories to areas explicit for the agro-food sector, such as food waste, or include other areas out of scope for this paper, such as the impact of distributed symbiotic systems on vulnerable/indigenous/rural populations. Another limitation stems from the geographical proximity of the two cases. Further studies are needed for areas that do not share the features of the case studies' locations, i.e. not characterized by cool climates, good transport infrastructure and stable governments. Additionally, risk management implications for the national and global policy makers to aid in addressing climate change issues is an interesting area for further studies.

A more detailed reflection of the various risk categories and alternative production forms reveals different risk profiles for different alternatives, implying that the best total system resilience may be a combination of production methods. The plans for deployment sketched out in the case studies illustrate the prolonged time scale for roll-out even on the local market, meaning that for the foreseeable future, all existing production forms will be needed to cover demand.

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Authors' contributions
TP collected the case study data and drafted the manuscript. MS developed the framework of the analysis and corrected and improved the manuscript. Both authors have read and approved the final manuscript.

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Availability of data and materials

See references. All cited data for the case RePro Food is available at www.Reprofood.com.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

As noted in the Acknowledgements, the authors are employed at companies involved in one of the cases. While we, the authors, at no time experienced that our respective employers attempted to influence the content of this research, or that we were constrained by the conditions of our respective employments, we wish to make clear our perspective to the reader. The research is based only on data in the public domain, available for the research community.

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