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An integrated theoretical framework to enhance resource efficiency, sustainability and human health in agri-food systems

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Abstract

The absence of integrated decision-making across the agri-food system is arguably the single biggest obstacle to global food security and breaking through it is perhaps our biggest challenge. To date little research has been done which takes a fully integrated view to address this global challenge. Integrated decision making implies change across all parts of the diverse agri-food system, requiring an integrated assessment of all the processes involved from the ecology of the land through to nutrition and health. To address this research need, we propose a theoretical framework for integrated solutions based upon mapping of whole agri-food systems, their quantitative analysis based on enhanced life cycle assessment, the use of emergent data to catalyse viable and commercially attractive innovation and the free access of data to all stakeholders and in particular consumers as the principle engine for change. This integrated framework is conceptualised through theoretical development building from prior research. This theoretical framework involves an iterative methodology of four overlapping steps (Map, Analyse, Visualise and Share), namely the MAVS cycle. It gives a transparent advanced methodology and collaborative decision support to all stakeholders across the agri-food ecosystems. We hypothesize that this framework would provide a mechanism to break down the current barriers that prevent the integrated solutions absolutely necessary for global food security. We also theoretically position the perspective that it would break the “four walls” of information that reside within each organisation, fostering an open system that encourages a more democratized agri-food system, in which sustainability and resource efficiency are embedded.

Keywords: Food security; Agrifood systems; Sustainability; Resource efficiency; Life cycle assessment

1 Introduction

Achieving food security will involve not only high productivity of nutritious food but also stability to changes in weather and markets, resilience to stresses and shocks, and equity in supply (Conway, 2012). Implicit is the notion of sustainability, meaning meeting the needs and aspirations of the present without compromising the ability of future generations to meet theirs, at the same time reconciling the environmental, social equity and economic demands (Ehrlich et al., 2012). Already, food insecurity is endemic because of many varied but compound causes that will be exacerbated by population growth and the climate change (Field et al., 2014). Current food supply systems and practices not only deliver insufficient food but are economically and environmentally unsustainable, lacking in resilience, inequitable and risk a human health disaster. A food system in which nearly one billion people are under-nourished and 1.5 billion are over-weight is at the very least testament to a massive system failure. The need for urgent action is widely recognised (Godfray et al., 2010; Baulcombe et al., 2009; MacMillan and Benton, 2014).

The projected increased demand for crop production ranges from 50% to 2 or even 3 fold increases depending upon the rate of global economic development and the type of future diets envisaged (FAO, 2009, 2012). Increases in production of this magnitude using current agricultural methods would greatly increase consumption of natural resources and be unsustainable. The “holy grail” for future agriculture is therefore sustainable intensification achieved by means of new agri-technologies (Baulcombe et al., 2009; Garnett et al., 2013). However, given the huge waste of both product and resource across the agri-food system (West et al., 2014), and the impracticality of some of the estimates of the required increase in production (which could exceed the primary productive capacity of plant earth) (Smil, 2013), there is an alternative system view to address this grand challenge: food security via increased resource efficiency. Thus, the challenge is not only about producing more food, but about ways to improve resource efficiency integrated throughout the diverse configurations of the global agri-food system, both in terms of food production *and* food consumption.

Integrated action in the agri-food sector would be unprecedented. Indeed, there is currently almost the complete opposite of an integrated agri-food sector, which in fact works in a fragmented manner. Farmers grow crops, manufacturers make food, retailers sell it, users waste and consume it and society (and the planet) pays the consequences. The organisations across the agri-food system are not integrated in their decision-making because the market does not work in that way and the supply chain boundaries encourage sub-optimisation at the whole system level. The supply chains for many food products are of such complexity that, beyond the layer of primary suppliers, they are unknown even to the businesses involved (O'Rourke, 2014). Defining what is sustainable and resource efficient becomes difficult in the face of this complexity and the implementation of genuine (rather than symbolic) and effective practice to bring this about is seriously impaired. Cross-sector relationships that do exist between these sectors are usually driven by cost alone and can exacerbate adverse environmental and health impact, for example by promoting increased use of some resources and agrochemicals, increased waste and excessive consumption of unhealthy foods. The effects of this fragmentation are also evident in the “unforeseen consequences” of actions such as regulations concerning pesticide use and other adverse impacts of many well-intentioned aspects of agriculture and food policy.

The absence of integrated decision-making across the agri-food system is arguably the single biggest obstacle to global food security and breaking through it is perhaps our biggest challenge. Following a recent detailed report which described the complexity of the agri-food system and stressed the need for the development of integrated approaches (IOM and NRC, 2015), in this paper we present a theoretical framework designed to meet this challenge; we suggest an integrated assessment of all the processes involved in the production and consumption of food, from the ecology of the land through to nutrition and health, thereby enabling increases in the resource efficiency of whole agri-food systems.

2 An iterative methodology for integrated decision making in agri-food systems

The theoretical framework for improvement of agri-food systems is based upon mapping of whole agri-food systems, their quantitative analysis based on enhanced life cycle assessment, the use of emergent data to catalyse viable and commercially attractive innovation and the free access of data to all stakeholders and in particular consumers as the principle engine for change. It is an iterative methodology involving four overlapping steps (Map, Analyse, Visualise and Share, the MAVS cycle), as shown in Fig. 1.

Fig. 1 The MAVS cycle, a novel 4-step methodological iterative process to achieve optimised interventions to increases the sustainability and security of agri-food systems.

2.1 Map complete agri-food systems as ecosystems

Making descriptive maps of complete agri-food systems is the essential first step. Extension of the agro-ecological approach (Conway, 1987) to encompass entire food production and consumption chains provides the framework. The *agri-food ecosystem* has defined system boundaries in which all the processes and actors are described and quantified. All agri-food ecosystems have four key elements (Fig. 2): 1, agricultural and land-use strategy; 2, crop (or livestock) production and harvesting; 3, processing, storage and distribution; and 4, retailing and consumption. The actions of key stakeholders, the farmers, the agri-businesses, the food producers and retailers, and consumers can be represented, together with external factors specific to a particular commodity or geographic location. For each specific agri-food ecosystem, waste and losses can then be depicted together with the environmental and health penalties. This ecosystem approach is applicable at a range of scales, from global to local, from populations to individuals, from single commodities to specific foods. It is applicable to all geographic locations.

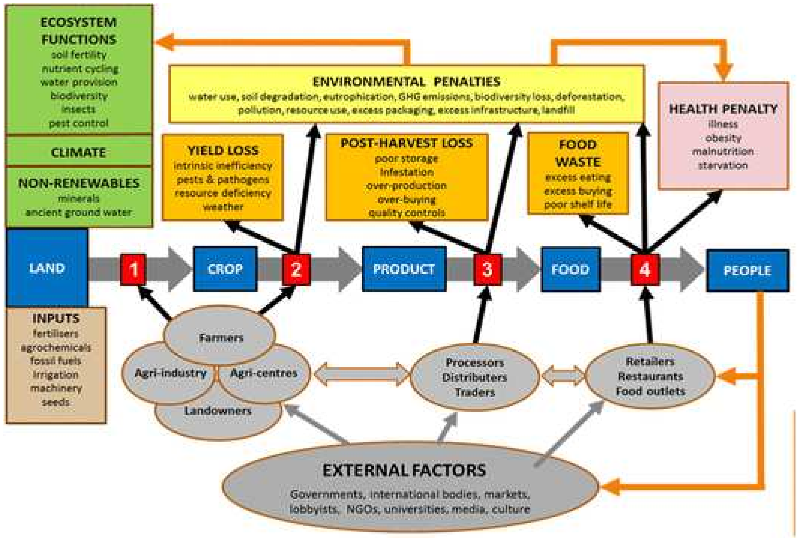

Fig. 2 A generic agri-food ecosystem template, showing: its four principle components; the ecosystem functions, climate, resources and inputs that drive the production system; the key actors and external influences; the losses and wastes; and environmental and health penalties. Also shown are two feedbacks (orange lines) – from environmental impacting on the functions on which the system depends and from people, the consumers, who can influence agri-food businesses, farmers, politicians, etc. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

What is needed for this mapping process is the development and adoption of a common language for description and a consistent approach to parameterisation. Progress has been made in this regard in various industries through foot-printing exercises and other procedures but these are limited in scope and take-up is patchy (O'Rourke, 2014). Research is urgently needed to find compatible measures of resource efficiency, environmental impacts and effects on human health (IOM and NRC, 2015). These need to be comprehensive and most importantly appealing to all parties in the agri-food ecosystem.

Parameterisation of waste is the first challenge. Because waste occurs throughout the agri-food ecosystem, at every step in the food supply chain, it is necessary to describe and quantify it in a way that allows comparison and evaluation of impact within the whole system. It is useful to define two types of waste. Firstly, the waste of inputs such as water, fertiliser and fuel due to their inefficient use. This type of waste would be rectified by innovations such as: precision agriculture to reduce water or fertiliser use, or selectively kill weeds; and more efficient logistics in the supply chain to reduce energy use.

The second type of waste is the incomplete conversion or processing of materials as progress is made down the supply chain, from crop production to food consumption. In essence waste of this type is best defined in terms of the losses that arise from the primary processes of crop plant growth all the way to the nutrition of a healthy human body. One could calibrate this in terms of units of mass, energy or a particular nutrient such as N. In crop science there is a long tradition of expressing biomass yields in terms of “use-efficiencies” together with various indices of conversion (Monteith, 1977), and we suggest such methodology could be applied to describe waste over the whole supply chain. For example, Radiation Use Efficiency (RUE) defines how much plant biomass is derived from a unit of incident solar radiation; in all plants, this is well below the theoretical limit and represents the first loss (waste) in the system. Harvest Index (HI) then defines how much of this biomass is converted into usable yield (e.g. grain), this trait being one that has been maximised through plant breeding. The physiological attributes of crop plants fix the maximum values of RUE and HI to set the yield potential, whereas agronomic practice and environmental conditions determine the actual yield. The resultant yield gap, the difference between potential and actual yield, is defined as a loss (waste) in the agri-food system. This rationale could then be extended to the losses during the harvesting and processing of the product into a food-stuff, its distribution to retailers, and its purchase and consumption by the consumer. Finally, and perhaps most controversially, the fraction of that consumption necessary for good health has to be determined. Already exciting progress has been made in this regard, redefining agricultural yields in terms of people nourished per hectare (Cassidy et al., 2013). Reducing waste is possible by interventions at all steps, including: the genetic improvement of plants to increase yield potential; improved agronomic practice to reduce the yield gap; improved distribution and storage infrastructure; and altered patterns of consumption by the consumer.

Environmental impacts arise from activities across the food supply chain and will include water over-use, soil carbon loss, soil aggregate loss, nutrient depletion, fertiliser leaching, de-forestation, biodiversity loss, effects of pesticide run-off, tropospheric ozone concentration increase, soil methane and N_2O release, and CO_2 emissions. These combine and can deplete what is considered natural capital, which is obviously connected to a much wider supply chain. We need to describe, measure and understand whole supply chain resource sustainability and not just a single resource sustainability or the sustainability of any particular part of the supply chain. Implicit in this consideration are the processes which re-use and recycle waste so as to help reduce and/or replenish the consumed natural capital. Considerable progress has been made in the quantitative evaluation of environmental impacts of agriculture, in particular through the monetization of ecosystem services (Bateman et al., 2013), which can be extended across the whole agri-food ecosystem. Particularly interesting is the idea of developing indices of environmental impact such as a sustainability index for a particular supply chain (O'Rourke, 2014). There is clearly an urgent need for consensus-building across the agri-food sector to establish widely applicable environmental impact indicators (Hellweg and Canals, 2014). The obvious barriers to this consensus arise from the very fragmentation of the agri-food system that our methodology is aiming to rectify.

Relationships between diet and health are well-established and huge volumes of relevant data exist. To describe health impacts in terms of resource efficiency nevertheless represents a new challenge; for example: we need to connect an increment of food waste such as yield gap or loss from deterioration during storage to a unit measure of health impact from under-nourishment; and we need to quantify the ill-health impact from each increment of “wasteful” over-consumption. The parameterisation of food consumption, human health and nutrition in terms of whole system agri-food sustainability is thus a radical shift in thinking. Again, consensus is needed on how to develop such indicators, and there is likely to be resistance because health and nutrition are almost always considered separately from the issues related to environment, agriculture and food production. However, recent work that clearly demonstrates that global diets link environmental sustainability and human health, provides a strong argument that these distant parts of the agri-food system have to be considered together (Tilman and Clark, 2014).

2.2 Analyse agri-food ecosystems using transparent and dynamic decision support tools

Whilst mapping and quantisation of complete agri-food ecosystems is of great value, it is inadequate, and has to have built upon it an analytical methodology to aid decision-making. All of the sub-components of Fig. 2 have been variously modelled and analysed, most often on a global scale (e.g. Foley et al., 2011) and frameworks put forward to provide a systems perspective (Hammond and Dube, 2012). Generalised solutions are vital in forming over-arching recommendations in national or global reports, but may not fulfil what is needed in a practical sense. There is a vast number and huge diversity of agri-food ecosystems: each crop in each farm; each food and its myriad of ingredients. An integrating methodology is required that can be routinely applied to specific local agri-food ecosystems (IOM and NRC, 2015). A number of quantitative methods are suitable for this purpose including Life Cycle Assessment (LCA). LCA has already been applied to food supply chains (Garnett, 2014) and is used widely in a variety of industries to track environmental impact (O'Rourke, 2014; Hellweg and Canals, 2014). Hybrid LCA methods seem particularly attractive (Guinée et al., 2011) since these integrate two LCA components (traditional or process LCA and environmental Input~~-~~–Output LCA) in order to make use of their respective advantages. Traditional LCA is based upon a cradle-to-grave analysis of all supply chain inputs (that is, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, ~~and~~ disposal or recycling, etc). Environmental input–output LCA takes an economy-wide perspective of environmental assessment, the whole economy being taken as the system boundary so that every input and associated impact from any given sector of the economy that contributes to the supply chain can be estimated. Environmental input–output LCA therefore offers the advantage of an extended system boundary that is essential for analysis of agri-food ecosystems as defined above.

One example of this hybrid LCA methodology is the Supply Chain Environmental Analysis Tool (SCEnAT), which is compliant with ISO14040 and ISO14044 international standards (Koh et al., 2012) and has a proven decision support cycle (i.e. map, calculate, intervene, evaluate and decide cycle) that has been replicated and tailored to different levels of stakeholders and decision makers. Hybrid LCA tools such as SCEnAT thus provide the methodological foundation for a transparent and dynamic decision support tool to analyse agri-food ecosystems. It would be extended to include a range of outputs to quantify resource use, waste, environmental impact and health effects, measured according to the criteria set out above. This development would require incorporation of agronomic methodologies into LCA design. Without guidance from crop science, the advanced LCA methodology may be incomplete in its incorporation of biological processes or agronomic practice. Integration of the methodology in the decision support to enable analysis of human behaviour in food consumption and of health impacts is a particularly significant challenge as discussed above. However, consumption effects can be modelled such as those that determine food preferences, toxicology impact, health penalties and benefits. These can be quantified across the food chain in a unified way that allows novel monetization (including ethics, justice and equity along with the triple bottom line indicators), whilst demonstrating the dynamic ripple effect across the agri-food ecosystem as a result of decisions made by the consumers.

Advanced hybrid LCA is a routine, visible, accessible tool that will provide realistic and practical outputs, applied to individual agri-food systems. Furthermore, it can be integrated with various supply chain modelling and optimisation capabilities, such as systems dynamic simulation modelling, discrete event simulation, agent based modelling, analytical hierarchy process modelling, and uncertainty modelling (Matos and Hall, 2007; Taplin et al., 2006; Börjesson and Tufvesson, 2011; Acquaye et al., 2011, 2014; Bai et al., 2012; Koh et al., 2013).

The application of advanced LCA across a complete food supply system requires accurate data from many sources, presented in useable form. This can present significant limitations and problems for the application of LCA. Key data may be missing and resultant gaps filled from databases, requiring various assumptions. Tilman and Clark (2014) showed that whilst there was abundant data for LCA of GHG emissions for “cradle to farm-gate” few data was available on emissions from post farm-gate activities (processing, packaging and transportation to households). The challenge of obtaining complete data sets is even greater because the analyses of resource use, waste, environmental impact and health penalties require~~s~~ a much broader spectrum of data than GHG emissions alone.

2.3 Visualisation of impact indicators by all stakeholders in the agri-food sector to catalyse innovative and appropriate solutions

The scenario modelling capability (i.e. contextuality) of advanced LCA allows simulation of changes and interventions. This would enable the best interventions and changes, predict their outcomes and aid decision-making with respect to the inevitable trade-offs between these outcomes. For instance, scenario modelling can answer questions such as: where are the pressure points or sites of greatest sensitivity to change and thus the targets for intervention; what new genetic trait in a crop would be most beneficial for a specific agricultural and socio-economic context; what might be the effect of a change in a particular aspect of consumer choice on crop production and resource use; what would be the implications for the food producer, retailer and consumer of a change to a more sustainable and resilient crop production, through a new plant variety or altered agronomic practice; where are the hotspots in terms of resource use, environmental effects or waste; how do we balance resource efficiency with the excess capacity needed for resilience; how do we optimise closing of yield gaps by the use of agrochemicals with their environmental impact; how do we adapt to climate change; what are the barriers to uptake of the required new technologies and their impact upstream and downstream across the ecosystem. The answers to these questions could be individualised for each stakeholder according to the huge diversity of crops, foods and locations, the types and sizes of farms or agri-business and societies in which they are embedded.

Clearly, it is a massive undertaking for LCA to become embedded in the operations of all of the diverse agri-food stakeholders. However, there are encouraging signs from other industries where application of LCA is becoming commonplace (O'Rourke, 2014). When the advantages of the integrated approach are proven, in terms of increased resource efficiency, reduced environmental and health impacts and lowered costs, the uptake of this approach increases. Through a dashboard displaying the impact indicators, each stakeholder across the agri-food systems becomes aware of its behaviour and decisions and the implications for other parts of the system and other stakeholders. We suggest that new and previously unthought-of solutions and interventions will arise from the whole system view. New collaborations and partnerships would result as the mutual benefits become clear.

However, heterogeneous interpretations of the same data could inhibit such constructive actions and prevent the desired beneficial outcomes. Studies adopting institutional theory show that information is understood differently according to professional norms (Dimaggio and Powell, 1983), and therefore, conflicts arise from completely different interpretations of the same facts between various stakeholder groups (Scheer et al., 2014). Institutional decoupling theory argues that institutional actors adopt heterogeneous information communication strategies (Meyer and Rowan, 1977). For instance, industry interprets risks against the backdrop of marketing and statutory regulations and use risk communication as a type of calming strategy (Scheer et al., 2014). Other studies have considered supply chain triadic relationships, applying structural hole theory (Burt, 1992). It is argued that it is in the interests of an actor to play a role of *tertius gaudens* or *tertius iungens* in order to derive benefits from a bridge position in triadic relationships (Choi and Wu, 2009; Li and Choi, 2009).

Clearly the pathway from data analysis to sustainable agri-food systems through integrated decisions making is fraught with problems that arise from its fragmented and disparate nature. New government policies of regulation, incentives and penalties, formulated through the same kind of evidence-based integrated analysis, will be needed. Moreover, as discussed in the next section, changes in public opinion and action will play a key role.

2.4 Share data, information and methodology widely and freely amongst farmers, agri-businesses and consumers

In the final step of the MAVS cycle, the decision support tool would harness the productive energy of its user-communities. LCA and subsequent analyses will generate vast arrays of data, analysis of which will be aided and enhanced with Big Data analytics (Gijzen, 2013), in the future through theoretical and experimental quantum computing (Howard et al., 2014). Integration and sharing of this data will be essential because sustainable food security demands multi-community research collaborations and information sharing not just within the business and its supply chains but also with governments, agricultural research centres and farmers. For instance, farmers hold vital knowledge and understanding of their own fields, climate conditions and agriculture practices; working through farmers and farmer organisations can channel effective environmental collaboration between formal science and local understanding (MacMillan and Benton, 2014; Pretty, 2008). Users would access innovative solutions from outside the organizational walls, allowing co-creation with external partners and connection with the outside world where knowledge is abundant (Chesbrough, 2010). Most importantly, the results of LCA should become accessible to consumers, offering novel opportunities for agri-food businesses to address their needs, by incorporating healthy, nutritious and green values into their customers “total experience”, an individualised personal “agri-food ecosystem”.

Already there is enormous activism throughout the world related to issues such as healthy lifestyles and reducing food waste, suggesting there are great opportunities for public engagement in the wider aspects of food security. Because businesses are standardizing information architecture and application programming interfaces, data exchange with third parties is becoming enabled (Shelton, 2013). Further enhancement through social media, could therefore promote the new types of collaboration and collective action vital for the transition to sustainable food security, driving behaviour change to re-shape the agri-food ecosystem. Innovative programmes bringing together science education and environmental education can help establish the conditions and learning processes needed for the cultural shift towards food security (Wals et al., 2014). Recent research has shown how people are willing to sacrifice personal gain to preserve resources for future generations when they are assured that others will do like-wise, decisions being made by majority voting effectively constraining selfish minorities (Hauser et al., 2014). Thus, policy makers in the public health sphere, in education and in the environment will be important catalysts of the transition to sustainable food security but only if they can adopt a behavioural approach that harnesses such social preferences.

3 Conclusions

In this paper, we present a theoretical MAVS framework which would give a transparent advanced methodology and collaborative decision support to all stakeholders across agri-food ecosystems. We hypothesize that it would provide a mechanism to break down the current barriers that prevent the integrated solutions absolutely necessary for global food security. We also theoretically position the perspective that it would break the “four walls” of information that reside within each organisation, fostering instead an open system that encourages a more democratized agri-food system, in which sustainability and resource efficiency are embedded.

Research is now needed to rigorously test the feasibility and practicality of this theoretical framework, and the suitability of the methods we propose. Such research would include a detailed analysis of a single supply chain, such as cereal crop, tracing all the events from crop growth through to production of a product, and its distribution and sales through a retailer to the consumer. Other studies would start at the consumer end, to consider how changes in consumer choice, informed by evidence and data, as indicated above, feed through the system to affect the manufacturer, farmer and landscape. Comparisons would be made between different contexts – for example between low income and high income countries, or between farms using different agronomic practice. There are many obstacles to overcome in such research, including access, sharing and harmonisation of data as well as parameterisation of social and health aspects as we have indicated. But, because sustainability is now an issue of concern to all the stakeholders in the agri-food system, this research is not only urgently needed but also very timely.

Uncited reference

Royal Society, 2009.

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Highlights

- A theoretical Map, Analyse, Visualize and Share integrated framework is proposed.
- The framework promotes a transparent methodology for collaborative decision support.
- A mechanism to break down barriers that prevent integrated solutions is suggested.
- An open system embedding sustainability and resource efficiency is fostered.

Queries and Answers

Query: Please check all the affiliations.
Answer: Yes. For b, please add 'and Advanced Resource Efficiency Centre', before The University of Sheffield. The rest of the affiliations are correct. Thank you!!

Query: The spelling of the author name in the text has been changed from "Garnet" to "Garnett" to match the reference list. Please check the spelling here and in subsequent occurrences, and correct if necessary.
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Answer: Yes. Checked. All correct and consistent. Thank you!!

Query: References Baulcombe et al., 2009 and Koh et al., 2013 are cited in the text but not provided in the reference list. Please provide them in the reference list or delete these citations from the text.
Answer: Please delete the Baulcombe reference in the text. The reference for Koh et al, 2013, is actually 2012. This is already in the reference list. Thank you!!

Query: The spelling of the author name in the text has been changed from "DiMaggio" to "Dimaggio" to match the reference list. Please check the spelling, and correct if necessary.
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Query: Uncited reference: This section comprises reference that occurs in the reference list but not in the body of the text. Please position the reference in the text or, alternatively, delete it. Any reference not dealt with will be retained in this section. Thank you.
Answer: 'The Royal Society 2009' reference positions in the text would be at all the same positions where the reference of Baulcombe et al., 2009 was located previously. Thank you!!

Query: Please check the page range in reference Bai et al., 2012.
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