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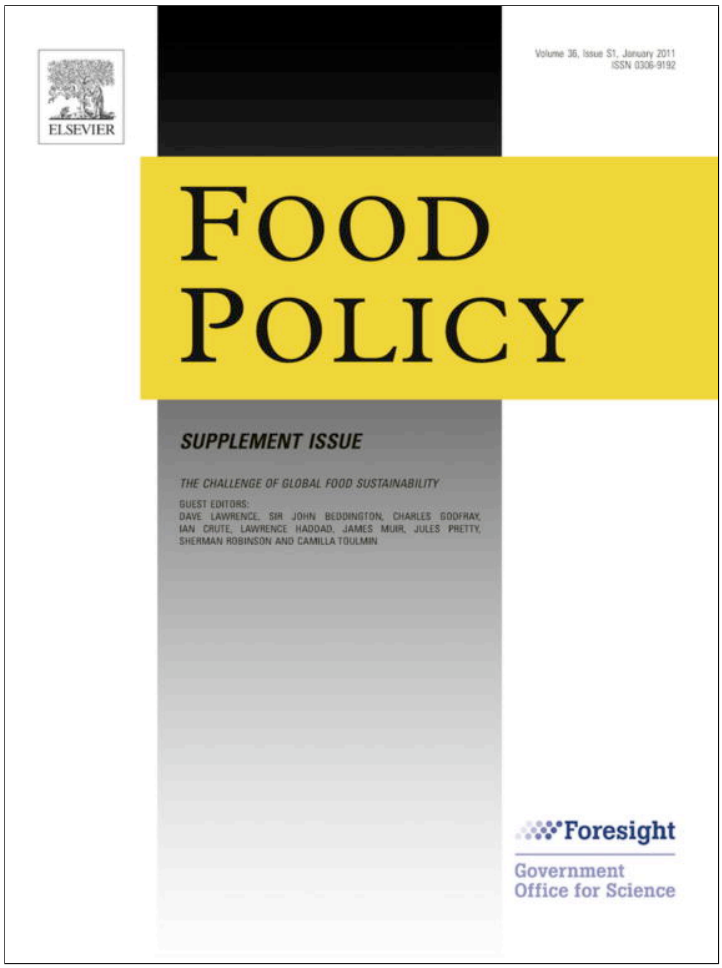

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Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? ☆

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ABSTRACT

This paper reviews estimates of food related greenhouse gas (GHG) emissions at the global, regional and national levels, highlighting both GHG-intensive stages in the food chain, and GHG-intensive food types. It examines approaches that have been proposed for mitigating emissions at each stage in the chain and looks at how these sit within wider discussions of sustainability. It finds that efficiency-focused technological measures, while important, may not only be insufficient in reducing GHGs to the level required but may also give rise to other environmental and ethical concerns. It gives evidence showing that in addition to technological mitigation it will also be necessary to shift patterns of consumption, and in particular away from diets rich in GHG-intensive meat and dairy foods. This will be necessary not just in the developed but also, in the longer term, in the developing world. This move, while potentially beneficial for food secure, wealthier populations, raises potentially serious nutritional questions for the world's poorest. A priority for decision makers is to develop policies that explicitly seek to integrate agricultural, environmental and nutritional objectives.

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Food chain GHG emission: an overview

The food chain produces greenhouse gas (GHG) emissions at all stages in its life cycle, from the farming process and its inputs, through to manufacture, distribution, refrigeration, retailing, food preparation in the home and waste disposal. At the farm stage, the dominant GHGs are nitrous oxide (N_2O) from soil and livestock processes (manure, urine and applications of nitrogen fertilisers) and methane (CH_4) from ruminant digestion, rice cultivation and anaerobic soils. Carbon dioxide (CO_2) emissions arising from fossil fuel combustion to power machinery, for the manufacture of synthetic fertilisers and from the burning of biomass also contribute, albeit to a lesser extent. However, CO_2 resulting from agriculturally induced land use change can add considerably to farm-stage impacts. Beyond the farm gate, CO_2 from fossil fuel use dominates, with a supporting role played by refrigerant gases (see Fig. 1).

Fig. 1 shows how the different GHG gases contribute to emissions at different stages in the food chain. The left half (lighter greys) of the pie chart denotes on-farm and pre-farm emissions, comprising methane, nitrous oxide and carbon dioxide from on farm processes (see discussion in 1). The pale grey 'bulge' on the left that expands the pie chart illustrates the additional, and hard-to-quantify emissions that arise from agriculturally induced land use change. The right half of the pie chart shows that post-farm gate emissions (from manufacturing, transport and so forth) are largely attributable to fossil fuel energy use, and, to a smaller extent, to refrigerant emissions.

While there are no studies that quantify GHG emissions arising from the entire global food chain, there have been estimates of GHGs attributable to global agricultural production. The IPCC estimates agriculture's direct impacts to stand at about 10–12% of global emissions (5100–6100 $MTCO_2$ eq); this excludes emissions resulting from fuel use, fertiliser production and agriculturally induced land use change (Smith et al., 2007).

The figure rises to up to 30% when additional emissions from fuel use, fertiliser production and agriculturally induced land use change are included; land use change alone accounts for 6–17% (Bellarby et al., 2008).

One regional analysis for Europe finds that food accounts for 31% of the EU-25's total GHG impacts, with a further 9% arising from the hotel and restaurants sector (European Commission, 2006). At the national level, developed country studies find food consumption contributes between 15% and 28% to overall national emissions (Garnett, 2008; Defra, 2009; Audsley et al., 2010; Swedish Environmental Protection Agency, 2010; Regional Activity Centre for Cleaner Production, 2008; Nieberg, 2009; Kim and Neff, 2009; Australian Conservation Foundation, 2007). Fig. 2 shows the breakdown of emissions at each stage in the supply chain for the UK food system. One UK study (Audsley et al., 2010) additionally quantifies emissions associated with food consumption-induced land use

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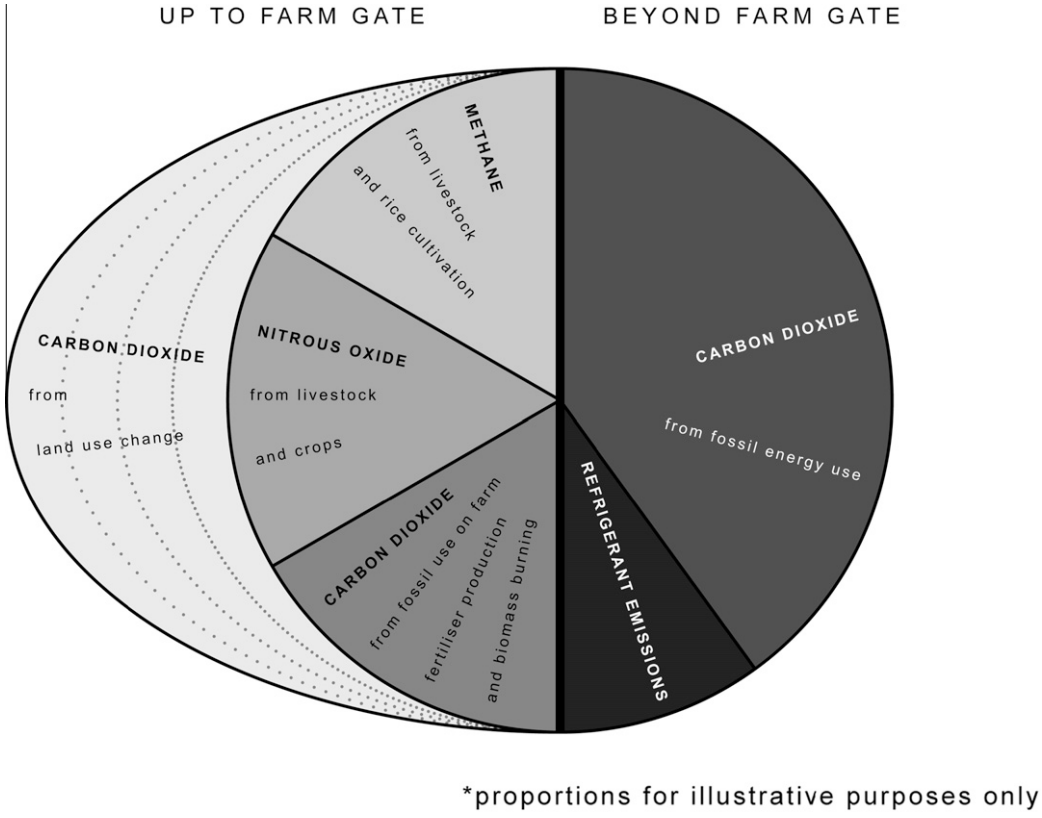

Fig. 1. Food chain impacts and the distribution of the different gases.

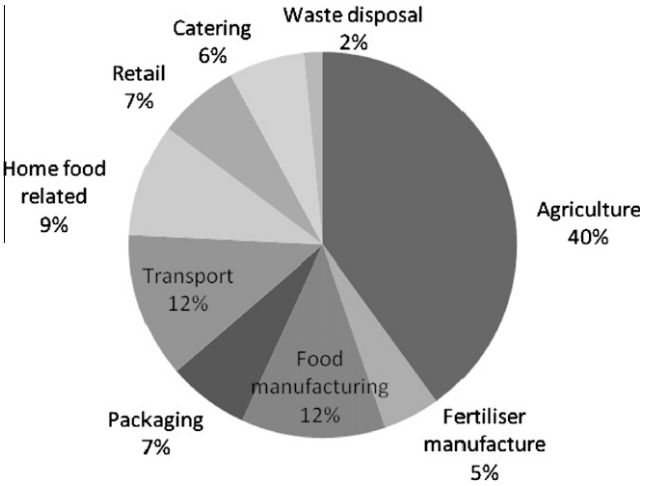

Fig. 2. Breakdown of food chain GHG emissions in the UK excluding land use change. Source: adapted from Garnett (2008).

change and finds that this increases the food chain's overall GHG contribution by 66%.

It is not possible to make meaningful comparisons between different countries. In absolute terms, food emission estimates vary due to differences in methodological approaches, the placement of boundaries, assumptions made and the quality of the data obtained, masking any genuine differences that may result from variations in biophysical conditions, fuel sources and consumption patterns. Moreover, food's relative contribution to country level emissions in relation to other sectors (such as transport), will depend on the GHG intensity of these other sectors.

In addition to country level estimates, there are numerous life cycle assessments of individual food products. These generally find that meat and dairy products, and air freighted foods, tend to carry the highest GHG burden (European Commission, 2006; Williams et al., 2006; Sim et al., 2007). When land use change impacts are included, the GHG contribution from livestock increases further (FAO, 2006; Audsley et al., 2010). These findings have a bearing on what can be done to reduce food chain emissions.

Reducing food chain GHG emissions: some options

The following paragraphs summarise the measures that have been proposed for reducing GHG emissions at the agricultural and post-farm gate stages respectively and highlight some broader sustainability issues that these approaches raise. The potential for mitigation offered by both technological improvements and behaviour change are examined.

The agricultural stage: technological and managerial approaches to mitigation

The literature here is vast, has been summarised most comprehensively by the IPCC (Smith et al., 2007) and broadly falls into five sets of measures:

a. *Enhancing carbon removals*: measures to restore degraded lands, afforestation, no or minimum tillage, the incorporation of organic matter.
b. *Optimising nutrient use*: precise dosage and timing when applying organic and inorganic fertilisers; incorporating nitrogen-fixing legumes into rotations.
c. *Improving productivity*: approaches that increase the yield of edible output per unit of emissions generated including:

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crop and animal breeding; feed optimisation and dietary additives; pest and disease management.

d. *Managing and benefiting* from the outputs: including manure and plant biomass: composting, and the use of anaerobic digestion.
e. *Reducing the carbon intensity* of fuel inputs through energy efficiency improvements and the use of alternative fuels such as biomass, biogas, wind and solar power.

None of these approaches, except perhaps (e), is entirely uncontested (and certainly not here either if first generation biofuels are used). The need to optimise fertiliser inputs (b) is widely accepted, although those committed to organic farming question the need for inorganic fertilisers per se (Soil Association, 2010), and some studies question the benefits of legumes in all contexts (Thorburn et al., 2010). Option d – making best use of the outputs – may prompt animal welfare concerns since manure collection is more readily achievable in confined rearing systems; a strong focus on linking anaerobic digestion to farming may add weight, in industrialising contexts, to arguments for the development of the intensive indoor systems (Nocton Dairies, undated) that many welfare advocates criticise.

However the greatest potential for trade offs, both environmental and ethical, arise from measures to increase soil carbon sequestration (a) and improve productivity (c). These are discussed in the paragraphs below (“Enhancing removals: soil and land carbon management” and “Improving productivity”). This section on agricultural production then concludes with a brief discussion of some less mainstream approaches to agricultural GHG mitigation and food security (“Non-mainstream approaches”) that have been proposed.

Enhancing removals: soil and land carbon management

IPCC, 2004 (Smith et al., 2007) estimates that there is vast potential for mitigating agricultural emissions through activities that sequester carbon in the soil. It estimates that agricultural emissions could technically be reduced or offset by around 5500–6000 $MTCO_2$ eq/yr (with a lower, but still significant economic potential of between 1500 and 4300 $MTCO_2$ eq/yr, depending on the theoretical cost of carbon); and, of this mitigation potential, 89% is achievable through soil carbon sequestration activities, largely taking place in the developing world. By comparison global annual agricultural GHG are currently 5100–6100 $MTCO_2$eq and so with a high carbon price, up to 80% of agriculture’s emissions today could be offset, mostly through sequestration – although not necessarily those of 2030.

However, while in many cases the incorporation of organic carbon into the soil will yield additional benefits such as improvements in soil quality and hence in crop yields, there can also be trade offs (Smith et al., 2007).

Some sequestration activities can undermine agricultural production. If, for instance, arable land is converted to grass or forestry for sequestering purposes, this may require more intensive cultivation in other areas to compensate for yield losses (with possible GHG consequences) or else trigger land clearance to grow food elsewhere. The relationship between the carbon and nitrogen cycles is complex and applications of organic or inorganic fertilisers to enhance carbon capture can increase N_2O emissions (Smith et al., 2007). There is also the risk of ‘sequestration swapping:’ where organic matter is applied to one land area, this can occur at the expense of other land which was previously receiving these applications and the net carbon gain is zero. Finally, soil carbon sequestration is not only reversible but time limited; once equilibrium is reached, no further sequestration occurs and the agricultural sector again becomes a net GHG emitter. Regarding other environmental impacts, the effects on biodiversity and water use are as yet unclear and probably mixed (Smith et al., 2007).

Ultimately, the potential offered by soil carbon sequestration can be judged from various standpoints. On the one hand, measures to increase soil carbon buy vital time for us to develop technologies and strategies to reduce fossil fuel emissions or – for agriculture – to develop nitrification and methane inhibitors. On the other, undue emphasis on sequestration may divert attention from the other main agricultural greenhouse gases – N_2O and CH_4. In particular carbon offsetting may appeal to the livestock industry which can use the soil carbon argument to play down the contribution that grazing animals make to N_2O and CH_4 emissions (Meat and Livestock Australia, undated). Most fundamentally a focus on carbon sequestration and associated offsetting activities can distract from the real challenge of tackling fossil fuel dependence and the consumption habits supported by it; offsetting from this perspective is simply a form of modern day ‘indulgence.’ (Pottinger, 2008).

What is clear though, is that avoiding further soil carbon losses is as important as actively seeking to sequester carbon. It may be helpful to consider soil carbon sequestration as an *outcome* of good agricultural management rather than a prime goal (Kibblewhite et al., 2008).

Improving productivity

Drawing from a growing research base (Smith et al., 2007), policy makers, opinion formers and the food industry emphasise the importance of increasing productivity as a route to GHG mitigation, the goal being to minimise both land requirements and GHG emissions per unit of product gained (Defra, 2008a; Royal Society, 2009; World Bank, 2009; EBLEX, 2009; Godfray et al., 2010). The ultimate goal is ‘sustainable intensification’ where yields are improved without damage to ecosystems.

However the concept of ‘sustainable intensification’ and the routes to achieving it can be the subject of much debate and may raise a number of environmental and ethical concerns.

In the case of crops, mainstream breeding approaches are geared to achieving pest and disease resistance, better nutrient use uptake and the partitioning of more energy into the grain rather than the stalk (Royal Society, 2009; Fedoroff et al., 2010; Tester, 2010). While such efforts are vital in order to halt land expansion and so minimise land use change related emissions, observers have pointed out that they may not be sufficient (Pretty, 2008) and can lead to social, economic and ethical trade offs. A focus on raising yields of the most commercially productive crops may mean that crops widely used by the world’s poorest and most marginal farmers are neglected (IAASTD, 2009; Lobell et al., 2008). Over-emphasis on a few key crops will reduce overall agricultural diversity and the system may ultimately become more vulnerable to pests and diseases. Moreover, a sole focus on edible outputs may fail to take account of the multiple uses that many rural communities make of crops; stalks are often used for animal feed and so their nutritional value is also important (Parthasarathy Rao and Hall, 2003). Finally, this breeding approach is predicated on the principle of “land-sparing” whereby intensive production takes place on as small an area as possible in order to maximise the land available for conservation or forestry. The effectiveness of land sparing strategies in a profit driven global market has been criticised; commentators have argued that it has not in fact been effective in preserving biodiversity nor in halting deforestation (DeFries et al., 2010; Vandermeer and Perfecto, 2006).

Since livestock utilise around 80% of the world’s agricultural land (FAO, 2009) and generate the bulk of the sector’s GHGs, there is a perception that efforts to raise livestock yields can generate both environmental and commercial benefits. For livestock in the developing world, measures to improve productivity include the

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use of improved fodder varieties in place of low quality grasses – an approach that can increase productivity while also improving livestock nutrition (Fodder Innovation Project, ongoing). The crossing of traditional breeds with higher yielding imported breeds can also raise yields although the latter will be less resistant to drought and other shocks, as discussed below.

However the more extreme breeding and feeding efforts that have taken place in the developed world, driven by cost motivations, raise both environmental and welfare concerns – and it is these systems that are expanding rapidly in emergent economies such as China and Brazil (Naylor et al., 2005). Strategies here have included breeding meat animals for rapid growth, increasing laying rates in chickens and raising milk yields in dairy cows to very high levels – on average over 7000 l/yr in the UK (DairyCo, 2010). Animal breeding developments have gone together with strategies to optimise the balance between the carbohydrate and protein content of the feeds, so as to maximise growth or yields while minimising nitrogen losses and (for ruminants), methane. In the developed world this has meant diets which include high levels of concentrates; these are generally less methanogenic than those based on grasses and coarse agricultural byproducts. However these diet formulations require the dedicated production of feeds such as cereals and oilseeds (particularly soy) and have given significant impetus to their global growth – a trend that is set to continue (FAO, 2009; Naylor et al., 2005).

Nevertheless, even when the additional land and inputs needed to produce grains and protein feeds are taken into account, intensively reared animals use less land than their extensively reared counterparts – since feed crops are more nutrient dense than grass, less area is needed for a given quantity of nutrition. Fewer GHGs (in particular methane) are also emitted. By contrast, extensively reared animals produce less edible output per unit of GHGs emitted, and have been largely held responsible for the bulk of livestock induced agricultural deforestation (FAO, 2006). Pigs and poultry require even less land and produce fewer emissions than ruminants, since their feed conversion efficiency is greater and methane is less of an issue. Moreover, since their growth and reproductive rates are higher, favourable genetic traits can be more rapidly introduced. Hence monogastrics appear more 'efficient' to produce than ruminants and are more profitable. Recent years have seen a rapid growth in production and consumption of pig and poultry products; this trend is anticipated to continue and is considered positive from a GHG perspective (FAO, 2009; Defra, 2010).

This is the rationale, but the productivity-oriented approach is open to challenge. At the herd level, breeding and feeding strategies that focus solely on very yields can cause health problems. Higher infertility and mortality rates in turn undermine the methane savings achieved since initially unproductive replacement heifers need to be reared to compensate (Garnsworthy, 2004). As such, from a straightforward life cycle perspective, a balance needs to be struck between productivity and other breeding objectives. Intensive rearing systems are also associated with other environmental problems including soil and water pollution (FAO, 2006; Naylor et al., 2005). Moreover, they can give rise to major animal welfare concerns. These include not only physiological ill-health such as lameness and loss of fertility but behavioural disorders and the inability to express natural behaviours (Webster, 2005; Fraser, 2008; Pew Commission, 2009). The justification of intensive production on grounds of carbon efficiency therefore raises serious ethical questions that cannot be ignored. If welfare is viewed simply as a rich world luxury that poor countries cannot afford then we may need to reconsider what we mean by the word 'development'.

Where breeding strategies are geared towards producing highly productive animals, less priority is placed on other traits such as their suitability for survival in less hospitable regions or climates, or on their ability to cope with a diverse range of feedstuffs. With climate change likely to give rise to greater unpredictability, it may be important to breed robust animals that can cope with variable circumstances and feedstuffs (Hoffman, 2010), even though they may be slower growing and emit more emissions.

A fundamental criticism of the productivity approach is that it does not take account of the differently appropriate qualities and functions of land use, or of alternative ways in which the very word 'productivity' might be defined – and it is based on the assumption that anticipated trends in livestock demand are inevitable and cannot be challenged.

Regarding land, while a combination of breeding and feeding strategies has led, in the developed world, to substantial reductions in emissions per kg of edible product, this very simple quantitative conclusion fails to take into account the fact that not all land types are 'equal.' With growing human populations, prime agricultural land for crop production (which supplies the bulk of our energy needs) is increasingly scarce. Instead of a narrow focus on yield per GHGs, a resource-sensitive approach might be to consider how different qualities of land might be most appropriately matched to our needs.

One view would be that feeding animals grains that could be consumed more efficiently by humans represents a sub-optimal use of prime arable land (UNEP, 2009; Garnett, 2009). Traditionally, livestock have been reared in mixed farming systems, or on poorer quality land that cannot support crop production. In mixed systems, livestock are grazed in rotation with crops, and input both dung and draught power to the system. Both grazing animals and monogastrics are also fed crop residues or food waste that humans cannot directly consume. Such an approach is resource efficient since inedible waste is converted into edible animal protein; in the absence of this transformation, humans would need to obtain an equivalent quantity of nutrition from elsewhere. That 'elsewhere' could either be existing prime agricultural land, where competition with grain production for human food consumption could arise, or on land deforested for the purpose. The use of poorer marginal and upland similarly represents a form of resource (including GHG) efficiency.

Moreover, if well managed, grazing livestock on pasture can yield other multiple benefits including the maintenance of ecosystem services and biological diversity. Some research suggests that grazing systems can increase soil carbon sequestration (Allard et al., 2007; Leibig et al., 2010) – but study findings are mixed (Gill et al., 2010) and any benefits will be time limited. However, although extensively reared livestock may yield resource efficiency and ecosystem benefits, these are only positive in a 'steady state' scenario, where no further expansion arises to meet growing meat demand and systems are managed properly. The last few decades have, however, seen major expansion in livestock production, leading to deforestation, grazing-induced land degradation (causing soil carbon losses) (FAO, 2006; Abril and Bucher, 2001) and the undermining of biodiversity (FAO, 2006). Hence the question of consumption trends arises, and is discussed in ''Changes in consumption''.

There are of course alternative approaches to 'land matching'. A different strategy, articulated in at least one study (Welsh Assembly Government, 2010), would be to use poorer quality lands for forestry and biomass. These stocks would sequester carbon and provide a source of renewable fuel. While the particular type of ecosystem that livestock farming has hitherto helped shape would be lost, the new plantings will give rise to a new type of ecosystem. The merits of this new ecosystem are likely to be judged as much by cultural and aesthetic as by scientific criteria. However, the food that was previously obtained from uplands will need to be produced somewhere else. This means that livestock will either need to be reared in more intensive systems and on better quality land

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elsewhere; or an equivalent quantity of plant based food for direct consumption will need to be grown instead. This alternative approach to land use logically leads onto intensive production, or to vegetarianism, or a combination of both.

These are only two of many possible visions of how land might be used. What is clear though is that how we judge different livestock systems depends on how we think about land.

This is also the case when making decisions as to how 'productivity' should be measured. The dominant life cycle assessment approach is to measure the volume of CO_2e emitted per mass of livestock product obtained. There are however other possible ways of measuring productivity. Table 1 lists some of them and tentatively suggests how different metrics might favour different livestock types or systems.

The choice of metrics, when combined with different assumptions about trends in demand, can give rise to different conclusions. If growth in demand for animal products is seen as inevitable, then the priority will be to deliver maximum output at minimum GHG cost: livestock here are problem whose impacts need to be, and can be, minimised. The logical outcome of this a shift towards intensive monogastric production.

However, if demand is seen as mutable, then it becomes possible to explore ways in which livestock can make a beneficial contribution to a sustainable, resilient agriculture. This view will see a greater role for grazing animals, combined with the feeding of pigs and poultry on byproducts. Livestock here are viewed as a positive benefit rather than just a problem to be managed – but the amount of meat and milk obtainable will be very much lower.

Finally, the different approaches to the question of productivity reveals differing attitudes to the characterisation of methane as a problem. Much of the rationale for improving ruminant productivity is so as to reduce methane emissions, which are estimated to account for 30% of CO_2e from livestock (FAO, 2006). Some argue that, given the imperative to reduce emissions in the short term, and in view of methane's high global warming potential in the first few years of its atmospheric life, it and other short lived gases should be a priority target (Moore and MacCracken, 2009; Ramanathan and Xu, 2010). This would increase the relative importance of addressing ruminant emissions (and those from rice).

Responses flowing from the prioritisation of methane include a search for methane inhibiting vaccines and feed supplements (O'Hara et al., 2003), arguments in favour of switching consumption from ruminant products to monogastric products (Weber and Matthews, 2007), and advocacy of vegetarianism or even veganism (Goodland and Anhang, 2009; Meat Free Monday, undated).

An alternative view sometimes found within the environmental movement (Fairlie, 2010) is that a focus on 'quick wins' such as methane abatement distracts from the imperative to tackle fossil fuel dependency. Current levels of atmospheric methane are certainly problematic but they have become so because of the scale and intensity of production – which has been achieved as a result of fossil fuel dependence. The problem of methane has ultimately been manufactured from, or catalysed by, fossil fuel use and it is this latter, rather than the former, that should be the priority target. An undue emphasis on methane justifies the further development of highly intensive rearing systems that are damaging in a host of ways. It has also been speculated that a landscape devoid of farmed ruminants could be repopulated with ungulates, which also produce methane (per comm., various).

In short, how people view methane reveals much about the ideological assumptions they bring to discussions about food emissions. Put somewhat simplistically, those who see methane as a pressing problem include both stakeholders with a strong faith in techno-industrial innovation and those who advocate veganism/vegetarianism for complex and not solely climate-related reasons. These stakeholders may differ in many important ways but one might hypothesise that on the whole their background tends to be either urban or (because of the scale of production advocated) at one remove from the land. On the other side are the apologists for methane who may be large scale farmers, pastoralists and their advocates, and environmentalists who argue for traditional agriculture (the latter generally argue that a reduction in livestock production is also needed). What they share is a strong sense of connection with the land and a rural, somewhat traditionalist perspective.

This analysis of the methane issue may be open to question but what is clear is that differences in how 'responsibility' for the problem of climate change is allocated do need to be explored if we are to achieve some sort of consensus as to the way forward.

Non-mainstream approaches

In addition to the mainstream mitigation approaches discussed above, a number of other routes to combining mitigation with food production are being explored. Some of these, including silvopasture and agroforestry, have been acknowledged by mainstream observers (Smith et al., 2007; World Bank, 2009). Others, although

Table 1
Different metrics for assessing GHG emissions and productivity.

	Comments
Quantity based	
kg CO_2 eq/kg product	Mainstream metric – favours intensive monogastric production
kg CO_2 eq/kg protein, iron, calcium, fatty acid profile and so forth	Depends on nutrient: iron and calcium metric may favour ruminants; grass-fed ruminants may have better Omega 3–6 ratios than cereal fed animals (Aurousseau et al., 2004; Demirel et al., 2006); protein as metric will favour intensive monogastrics
kg CO_2 eq/kg food and non-food goods provided (leather, wool, feathers, dung, traction)	Variable; on balance likely to favour ruminants
Area based	
kg CO_2 eq per area of land	Emissions lower for extensive systems and for monogastrics
kg CO_2 eq per area of prime arable land required	Emissions lower for extensive systems, both ruminant and monogastric
Resources based	
kg CO_2 eq/kg of fossil fuel based inputs	Emissions lower for extensive systems, both ruminant and monogastric
kg CO_2 eq avoided through use of byproducts or poor quality land to rear livestock; this approach quantifies the GHG and land opportunity cost of needing to obtain an equivalent quantity of nutrition from elsewhere	Favours extensive systems and particularly landless household pig and poultry reliant on scraps
kg edible output per given quantity of ecosystem services provided on farmed land	Favours extensive ruminant systems
kg edible output per given area of land 'spared' for conservation or biomass production	Favours intensive systems, especially monogastrics

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related to agroforestry and to each other, are less well known and include permaculture (Mollison and Holmgren, 1978), efforts to breed perennial food crops (Bell et al., 2008; UNEP, 2008) and the adoption of low external input systems of food production, including organic (United Nations, 2008). What these measures share is an attempt to close nutrient loops, build soil fertility and enhance on-farm biodiversity. In contrast with the 'land sparing' approach discussed above which focus on freeing as much land as possible for wilderness and other uses, these approaches seek to integrate the natural world into the human-made farmed environment. The effects of these practices on GHG emissions are unclear partly because the evidence base is slim and partly because much depends on the specifics of how farming is actually practiced. However, a number life cycle comparisons of organic and conventional farming in developed country contexts have been undertaken. The findings here are mixed; some studies conclude that emissions from organic systems can in fact be higher than from their conventional counterparts due to lower yields per unit of input (Williams et al., 2006) while other studies argue that organic and low input systems can be an effective route to mitigation (Niggli et al., 2009).

Non-mainstream approaches that are consistent with the land sparing paradigm include the theoretical development of highly intensive, virtually landless 'vertical farms' (www.vertical-farm.com). Still at the conceptual stage these closed systems would ideally generate their own energy (through anaerobic digestion, solar and other means) and recycle water and nutrients. Since no such farm has yet been built it is difficult to assess the feasibility or sustainability of the concept. However, major potential downsides include the welfare implications of highly intensive livestock systems, the significant technical challenges of producing enough energy to power and light the system, and the possibly massive negative impact on rural employment and livelihoods. Moreover, while feasible for fruits and vegetables it is very difficult to see how major commodity crops, such as wheat or rice, could be grown in these systems.

Beyond the farm gate: technological and managerial approaches

In the developed world, emissions resulting from activities beyond the farm gate account for approximately half of food chain emissions, and are fairly evenly distributed between the different stages (Fig. 2). Research into the developing world situation is unknown.

At the manufacturing and retailing stages, refrigeration is a major source of emissions and it has been estimated that in the UK alone (excluding the embedded 'coolness' in imports) it accounts for around 2.5% of the UK's domestically generated GHG emissions (refrigeration emissions are not represented separately in Fig. 2 as they are incorporated within the manufacturing and other stages) (Garnett, 2007). Measures to reduce refrigeration emissions include energy efficiency, the correct specification of new equipment, novel technologies such as trigeneration, action to eliminate refrigerant leakage and the use of alternatives to hydrofluorocarbons (HFCs). In other areas of retail and manufacturing energy use, mitigation measures include energy management, low carbon building design and the use of combined heat and power, wind, solar and biomass.

For transport, the options include: modal shift to less GHG intensive modes of transport, investment in more efficient vehicles, driver training, the use of information and communications technology for optimal route planning, vehicle sharing and backhauling.

Packaging measures include lightweighting and bulk importing; more recently there have been moves towards a more life cycle based approach to assessing the merits of packaging materials (Waste Resources Action Programme, undated-b).

Within the home, actions to address energy use include the purchase and use of A, A+ or A++ rated refrigerators, energy saving practices when cooking, and minimal use of the oven for single items. The introduction of smart meters may, by raising awareness of energy use, also lead to reductions, although the evidence base here is small and initial findings are cautious (Hargreaves et al., 2010).

Addressing food waste also offers considerable theoretical scope for emissions reduction. Wasted food represents a waste of all the emissions generated during the course of producing and distributing that food. Approaches to reducing food waste include better coordination and relations between manufacturers and retailers, voluntary industry agreements, public awareness campaigns and the development of packaging to extend product lifespans. For the European Union, a change in Animal By-Products regulations could enable more catering waste to be used for animal feed, so modifying the reliance on feed cereals and soy.

Ultimately achieving drastic CO_2 emission reductions will require a step change in national energy and infrastructure policies but in the meantime, many of the major manufacturers and retailers are already taking steps to reduce their emissions (Unilever, 2009; Cadbury, undated; Nestle, 2009; Sainsbury, 2009; Tesco, 2010). Many food companies are also assessing the sustainability of their sourcing strategies (largely due to NGO pressure), and have started to avoid the use of ingredients such as beef, soy (The Guardian, 2006) or palm oil (WWF International, 2009) that are directly linked with deforestation. A growing number have also undertaken carbon footprints of their products.

To summarise, at the post-farm gate stage, the main options for reducing food chain emissions are as follows:

- *Energy efficiency*: good management, correct sizing and use of equipment, use only when necessary; cleanest transport option practicable.
- *Cleaner and renewable fuels*: biomass, solar, wind, purchased green energy, combined heat and power.
- *Resource efficiency*: reducing unnecessary use of products and equipment; recycling and reuse where environmentally appropriate.

However, it is important also to consider the social, cultural, economic and geographical context within which these improvements are applied and to see what unintended consequences might arise.

Regarding food waste, if people waste less food, they will save money which they might use to upgrade to more expensive food products (perhaps air freighted foods, or more meat), or to buy other products or services such as clothes, electronic equipment or holidays, all of which have an environmental impact. Manufacturers and retailers who sell less food will seek alternative ways of making a profit; these might include diversifying into value-added products, selling more non-food goods or seeking overseas markets. In the absence of measures to address the effects of ever increasing consumption of all goods and services – not just food – (Jackson 2009), it is hard to see how reductions in food waste alone will lead to an overall decline in GHG emissions.

This rebound effect can also be found in the use of refrigeration. Models predict that with efficiency gains, refrigeration-related emissions are set to decline (MTP, 2006). However, these predictions need to be set in the context of a growth in societal dependence on refrigeration. In 1970, over 40% of the UK population did not have a fridge, and only 3% owned a freezer (Environmental Change Unit, 1997); today, ownership is virtually universal in the UK and in much of the developed world. The drivers that led to the growth in today's refrigeration dependence are complex (Garnett, 2007) but what is striking is that cold-chain developments

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have gone hand in hand with a shift towards the production and consumption of more inherently refrigeration dependent foods. For example, while the overall quantity of vegetables eaten in the UK has not changed much since the 1970s, the varieties we prefer to eat have – we consume more salads, berries and perishable, highly cold-chain dependent foods, while eating relatively fewer of the brassicas and root vegetables (except in processed or pre-prepared form) that are more amenable to non-refrigerated storage. Even the latter are likely to be kept in refrigerated conditions up to the point of sale. Moreover the ubiquitous presence of refrigeration has fostered the manufacture of new products that are inherently refrigeration-dependent such as fresh pasta, ready meals, ice creams and chilled and frozen desserts. Cold chain technology is now embedded in each stage of today's food system; its ubiquity means that new food products and technologies emerge that are predicated on refrigeration and so increase our refrigeration dependence.

There is, moreover an interesting relationship between waste and refrigeration (Garnett, 2007). In rich countries, a high proportion of the food people buy is wasted (Waste Resources Action Programme, 2009; Hall et al., 2009). This is not for want of refrigeration but is rather a consequence of the lifestyles we adopt, the relatively low proportion of our incomes we spend on food, and our attitudes in general to waste. This, in combination with our preference for perishable, refrigeration dependent food, means that we now waste food not only *despite* our refrigerators but almost *because* of them. As such, technological improvements in refrigeration should be set in the context of behavioural trends that are hurrying us in ever more refrigeration-dependent directions.

Regarding transport, one of the findings of life cycle analysis is that food transport makes, on average, a relatively minor contribution to overall food chain emissions (AEA Technology, 2005; Defra, 2008b; Edwards-Jones et al., 2008) although this will vary by food type (Sim et al., 2007). A shift to more local sourcing is seen as relatively ineffective and even counterproductive as trade offs can occur with emissions at other stages in the food chain. These LCAs have been useful in highlighting the need to tackle the food system as a whole – and in particular, the agricultural stage – rather than fixating on one particular issue. But in challenging the food miles assumption, the risk is that the role of transport in shaping economic developments and cultural norms is ignored.

For example, long distance transport has made possible scales of production that are themselves, from a GHG perspective, problematic. The intensification of animal production in twentieth century America was driven by two technological developments: the road system that allowed animals to be transported long distances, and refrigeration, which meant that meat and dairy products could be stored (Fraser in Zollitz et al., (Eds.) 2007). In this case, the combination of these two technological improvements catalysed the significant expansion of an industry that itself has a high GHG footprint; an example of the 'seeding' role of fossil fuel use as highlighted in the methane discussion (''Improving productivity'').

Furthermore, as supply chains continue to globalise, there will be more transport which (in the absence of a green fuels revolution) will lead to an absolute growth in emissions. This growth in mileage has gone hand in hand with infrastructural, systemic changes that bring with them their own impacts. As supermarkets and manufactures commit to securing supplies or locating their manufacturing plants far from home, their decisions give impetus to further investment in new or expanded infrastructure – roads, ports, runways, air freight handling facilities – as can clearly being seen in the emerging economies. While these construction activities will produce their own direct environmental (including GHG) impacts, more importantly, they foster a situation where supply chains become committed to, and predicated on, long distance sourcing and distribution. The presence of new infrastructure makes it easier and cheaper to source from further afield and of course the cost of investment needs to be recouped. By contrast, sources closer to home may be considered less economically attractive because labour costs are higher even where they may be environmentally preferable.

It can also be argued that long distance food transport serves as a marker for land use elsewhere. One might question the appropriateness in the long term of using scarce land in poor countries to meet the demand for luxury products in the developed world, notwithstanding important immediate benefits for poverty reduction (MacGregor and Vorley, 2006).

Finally the combination of complex technologies including transport, refrigeration, manufacturing and information technology has created a developed world food system that is based on the availability of a vast range of products that are of a consistently high quality and are ubiquitously available. Developed world consumers have come to expect no less. However, this abundance of choice may itself have environmental implications. More products require more space to display them; hence bigger stores with more lighting, heating and refrigeration. The imperative to produce many different varieties of the same product (different flavours of yoghurt), reduces the efficiency of the production plant as equipment needs to be shut and washed down in preparation for the next line. Greater choice can lead to overpurchasing (Kahn and Wansink, 2004), which in turn generates waste. Importantly, the choice imperative means that products have to be available whatever the season. We no longer accept the simple non-availability of tomatoes in winter but instead concern ourselves with assessing the relative merits of Spanish produce versus their UK hot-housed equivalents (Defra, 2008b). Non-availability is not an option. In short, discussions about the merits or otherwise of local sourcing cannot be reduced simply to carbon comparisons. The role of transport in fostering structures of production and habits of consumption need also to be considered.

To conclude, the nexus of technologies that characterises and has created our modern food system has had an important role in shaping our food habits and expectations. Hence technological approaches to achieving emissions reductions within transport, manufacturing and refrigeration need to be assessed in terms of the extent to which they foster a shift towards, or away from, further reliance on energy using technologies.

Changes in consumption

A growing body of research suggests that if we are to achieve substantial reductions in food related GHG emissions, then we must address not only how we produce and distribute our food, but also what it is we eat. In particular, a number of environmental studies have focused on the need to reduce consumption of meat and dairy foods (Goodland, 1997; Weber and Matthews, 2007; Stehfest et al., 2009; Garnett, 2009; Audsley et al., 2010). While substantial scope for mitigation via technological means has been identified both at the global (Smith et al., 2007) and country (ADAS, 2009; Moran et al., 2008) levels, their estimates of the reductions achievable do not factor in future growth trajectories. For example, while the IPCC identifies significant mitigation potential for agriculture, when set against the totality of agricultural emissions (both direct and land use related) the reductions achievable (even assuming a high carbon price) only amount to about 30% of the total impact. What is more, since food production is set to increase, absolute emissions will grow, while the opportunity for further sequestering carbon in the soil will dwindle. Hence the conclusion that we need also to moderate our consumption of livestock products seems inescapable.

The obvious response would be to target the very high levels of per capita consumption in the developed world. This however,

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while essential, may not be sufficient: a very simple analysis of the growth trajectories reveals that a reduction in rich world meat intakes alone will not reduce the anticipated increase in livestock production (Garnett, 2009). There are far fewer people in the developed than in the developing world and even though the former's per capita intakes are very high, the effects of cutting consumption here are minimal in the face of the large absolute projected increase in developing world consumption. This is true even though developing world per capita intakes are anticipated to remain modest.

Therefore, not only will rich world populations need to cut their meat and dairy consumption very substantially, but in addition, developing world peoples may need to moderate the increase in their per capita intakes.

However a low-meat global scenario raises nutritional (not to mention implementational) challenges. In theory, a diet with very moderate, or even no animal source foods can be healthful, if well planned (American Dietetic Association, 2009), but all depends on the context of consumption. In developed and rapidly industrialising countries a reduction in consumption of animal source foods can lead to health benefits (Friel et al., 2009). On the other hand, in very low income countries, where access to varied food types is limited, and where there are serious problems of mal- and under-nutrition, animal source foods can make a critical difference to the nutritional adequacy of the family diet (Neumann et al., 2002). Seventy percent of the world's "extreme poor" rely on animal rearing for their livelihoods (FAO, 2009). Hence a context-specific approach to meat and dairy consumption is required – one that situates livestock farming within a policy framework that integrates agricultural, environmental and nutritional goals.

International environmental observers (UNEP, 2009; World Bank, 2009; CBD, 2010; UNEP, 2010), have highlighted the environmental impacts of high levels of meat consumption. Sweden is considering the role of animal source foods from environmental and health perspectives (National Food Administration, 2009) and the Danish Government (Ministry of Food, Agriculture and Fisheries, undated) states that a lower meat diet is 'climate friendly' – but no specific government recommendations or policies within high-income countries have been published as yet. At least one major UK retailer, however, has highlighted the greater environmental impact of meat on its consumer-facing website (Tesco, undated), an indication that in the UK at least, the discussion is becoming more mainstream.

Other shifts in consumption may also be beneficial. Some of the approaches suggested for developed world populations include: reducing food consumption in overweight populations; cutting food waste; consuming more robust and seasonal food; reduced consumption of 'unnecessary' foods (such as tea, coffee and chocolate); shopping on food or over the internet; and taking the time to plan when shopping for food (Edwards and Roberts, 2009; Garnett, 2006; Garnett, 2008; Sustainable Development Commission 2009).

None of these (except perhaps the last) is uncontroversial or unproblematic. Table 2 below lists these suggestions, ranks them by priority order and highlights some potential concerns they raise. Note that the focus here is on GHG emissions – a broader definition of 'sustainable consumption' will need to cover fish sourcing, nutrition and other issues.

To conclude this section: the evidence base on what a sustainable diet might look like is growing and research is also starting to uncover the motivators and drivers of consumption (Jackson et al. in Reisch and Røpke (Eds.) 2004). However, research into *how* changes in behaviour might be achieved is still in its infancy as compared with the multitude of studies that have addressed the technological potential for mitigation. This imbalance reflects the relatively low priority that policy makers have hitherto placed on behaviour

Table 2
Low GHG food behaviours. Source: adapted from Garnett (2008).

Priority	Action	Impact area addressed	Problems
High	Eat fewer meat and dairy products	N_2O and CH_4 emissions; lost carbon sequestration from possible land clearance overseas; fossil fuel use	Reductions in both UK production and imports will be needed or else the problem will be shifted overseas; risk that fish takes the place of meat in people's diets, so increasing pressure on fish stocks
High	Eat no more than needed to maintain a healthy body weight)	Eating more food than needed stimulates the production of more food than is needed, and hence GHG emissions	Risk that individual people are victimised; overconsumption of food needs to be situated within an overall approach to consumption and consumerism
Medium, possibly high	Do not waste food and manage unavoidable waste properly	Less food waste permits lower levels of food production	The waste issue raises structural, system questions that are linked to the whole *consuming less* debate
Medium	Eat seasonal, robust, field grown vegetables rather than protected, fragile foods prone to spoilage and requiring heating and lighting in their cultivation, refrigeration, and rapid modes of transport	Tackles areas of refrigeration, transport, food spoilage	Measures to reduce air freighted foods may clash with international development objectives
Medium	Prepare food for more than one person and for several days	Efficiencies of scale – reduced energy use	Requires a measure of pre-planning. Trends in how people actually live and average household size make this approach difficult
Medium	Accept different notions of quality	Less waste permitting lower levels of production	Food that is edible but deemed of lower quality or undesirable goes to food processing or animal feed, or can go for export, so it may not always actually be wasted
Medium	Accept variability of supply	Tackles the problem of needing to supply foods even when the environmental cost of doing so is high	Variability within a complex food system may lead to bottlenecks and knock-on impacts which in turn can contribute to food waste; this approach may require a simpler food chain than the kind found in the developed world – one where foods are less processed
Medium	Consume fewer foods with low nutritional value e.g. Alcohol, tea, coffee, chocolate, bottled water	These 'unnecessary' foods are not needed in our diet and need not be produced	Raises major questions around free choice. Many of these foods (tea, coffee, chocolate) provide livelihoods to vast numbers of people in the developing world
Medium	Cook and store foods in energy conserving ways; possibly smart metering	Energy use in the home	Simple to do; saves money; impacts limited but useful
Lower	Shop on foot or over the internet	Reduced energy use	Research into the benefits of internet shopping is cautiously optimistic Edwards et al. (2009)

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change as an approach to GHG mitigation – which in turn perhaps indicates their reluctance to question the inevitability and desirability of today's growth-consumption development model (Jackson, 2009). An ambitious programme of research is now needed; one that moves beyond social marketing approaches (Owen et al., 2007) – since it is clear that these alone will not suffice – to examine what fiscal, regulatory and infrastructural measures are required (White et al., 2009) to reorientate patterns of consumption.

Moreover, it will be important to investigate not only approaches to behaviour change in the rich world, but also how developing countries can be supported in evolving sustainable, nutritious dietary patterns that avoid the environmental and health problems associated with Western modes. An important priority will be to explore how developing country trends in consumption of meat and dairy products (particularly in the rapidly industrialising economies), can be modified.

Conclusion

The food system contributes significantly to global GHG emissions. All stages in the supply chain contribute, but on average the agricultural stage is the single biggest GHG emitter, while meat and dairy products are the most GHG-intensive food types.

Technological improvements, while essential, will not be sufficient in reducing GHG emissions. The combination of population growth and rising per capita anticipated consumption of meat and dairy products will undermine the cuts that technological and managerial innovation can achieve. Moreover technology does not occur in a vacuum; technological change can foster new and unsustainable patterns of consumption. Hence, if we are all to eat, while keeping within required emissions limits, then we will have to eat differently. Finally, while GHG mitigation is important, it is not the only priority. Measures to reduce food chain GHG emissions need to be assessed within the context of other social and environmental concerns. These include human nutrition, biodiversity, water use and animal welfare. For any given mitigation measure, decision makers will need to consider the extent to which it moves us away from, or towards, achieving a more resilient, healthful, and morally attentive system of food production and consumption.

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