Feeding Nine Billion in a Low Emissions Economy: Challenging, but Possible

A Review of the Literature for the Overseas Development Institute

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The views and judgments expressed here are, however, not necessarily those of Oxfam, the Overseas Development Institute, those commenting, but are those of the author.

Contents

Abbreviations

CH_4	Methane
CO_2	Carbon Dioxide
FAO	Food & Agriculture Organisation of the UN
GHG	Greenhouse Gases
GTAP	Global Trade Analysis Project
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
NO	Nitrous Oxide

Units of measurement

M	Mega, 10^6, million
G	Giga, 10^9, billion
T	Tera, 10^12, thousand billion
P	Peta, 10^15, million billion
Gt	Gigatonne = billion tonnes
Pg	Petagram = Gigatonne = billion tonnes

Key points:

1. Agriculture is a very large emitter of greenhouse gases, more than quarter of all emissions when land conversion to farming is included. The share of emissions rises still further if those from the rest of the food system are included.
2. Developing countries are responsible for three-quarters of global agricultural emissions — with land use change included — and have the most rapid rates of increase.
3. Agriculture is unusual in that it has the scope for reducing net emissions to very low levels, at least for a period, by sequestering carbon in farming systems to offset gross emissions.
4. By 2050 it is expected that world population will reach nine billion. Assessments are optimistic that they can be fed, but increased production, whether by intensifying current farm land or expanding the area tilled, will increase emissions.
5. Given the scale of emissions in agriculture and the food chain, they will have to be reduced if global warming is to be held to two degrees or less. Yet to date there are few targets for reducing agricultural emissions: none globally, and only a few for countries.
6. So far, considerations of reducing agricultural emissions and of increasing food supplies have not been brought together. Hence it is still uncertain if the twin goals of producing more food and reducing overall emissions can be met.
7. That said, both the broad outline of measures, and in some cases the specific farming systems, needed to reduce net emissions are to a good extent known. There are, moreover, many local experiments that have yet to be fully documented that may offer useful lessons. Research and experience on ecological alternatives to farming that uses industrial inputs provides an important foundation for developing options.
8. Diet is a critical variable in these considerations: will the growing populations of the developing world, expected to become more affluent, consume similar levels of animal products to those seen in Europe and North America? Or can the world's population be persuaded to converge on a diet with lower consumption of animal products? This affects both the amount of food that needs to be produced — intensive livestock require feed grain and forage; as well as emissions, since it is difficult to reduce the amount of methane emitted by ruminants unless on certain perennial pastures
9. Two other points in the debate include: the extent to which intensification of current farm land can meet future needs with low net emissions, or whether substantially more land will be needed; and, the degree to which an increased proportion of the world's food supply is produced in temperate regions and exported to tropical ones, given that the former may be less hard hit by climate change impacts.
10. Last and perhaps most important of the considerations, are those concerning the distribution of food: if this is not equitably distributed and if large quantities are wasted, as currently applies, then more has to be produced if the hungry are to eat.

Summary

Background and aim of working paper

By 2050 it is expected that there will be around nine billion people in the world, more than two billion more than at present. Can they be fed? And can they be fed if climate change is to be limited to two degrees of global warming or less?

The former question has received considerable attention, the latter much less so. This has produced a notable gap between, on the one hand, arguments that stress the need for farmers in the developing world to raise production through higher yields per unit, relying heavily on increased irrigation, fertiliser application and intensive livestock production; and, on the other hand, the need for agriculture with lower net emissions.

Currently farming contributes more than 27% of the emissions of greenhouse gases (GHG), mainly from the use of fertilisers, fossil fuels for power on farms, numbers and management of ruminant livestock and flooded rice fields, and the conversion of habitats such as forest or peat land to fields and pastures that typically releases large amounts of carbon into the atmosphere. If climate change is to be mitigated sufficiently, then the practices that lead to such large emissions need changing.

There are, moreover, opportunities as well: since some farming systems sequester more carbon than others, there is scope not only to reduce emissions from farms but also to increase carbon storage, thereby cutting net emissions from agriculture to low levels — conceivably to zero.

But what would agriculture that mitigated climate change, and still fed nine billion in 2005, look like? What options are there for modifying existing farming systems and developing novel ones? These are the questions this short review of the literature addresses. This paper is based on a review of existing sources and consulting some key informants.

Overall, no studies were found that directly address the question; although such studies are, according to some sources, in the pipeline. There is plenty of evidence on how to feed the projected population without climate mitigation, as well as on current and future agricultural GHG emissions and approaches for their mitigation; but little that draws the two strands together.

This somewhat surprising finding apparently arises from the following four conditions:

- sector and discipline boundaries: net emissions reduction in agriculture requires a knowledge of agronomic and ecological processes that is not particularly prevalent amongst those working on food security and climate change;
- Research on reducing emissions focuses on solutions that are relatively large-scale, with direct commercial benefits — such as biofuels, and less on measures that are small-scale with no direct commercial return such as agronomic measures to lock in carbon;
- compared to other industries, agriculture is often and wrongly not seen as a major emitter of GHGs; and
- agricultural mitigation approaches are seen as being highly complex and locally specific, thus difficult to scale up. This probably overstates the difficulties and deters people from giving mitigation of farm emissions due attention.

Most studies treat agriculture as a matter of farm production, perhaps including as well the input industries that service farming. Others, however, look at the food system as a whole, including downstream transport, processing and storage of food.

In addressing the primary question, responses depend on how much current food systems are accepted — with inequalities of distribution, widespread malnutrition, obesity, high consumption of animal produce in OECD countries, food wastage on a large scale, and environmental unsustainability — or, how much plans are made for a future for a fairer, healthier, and environmentally sustainable food system.

Can nine billion be fed by 2050?

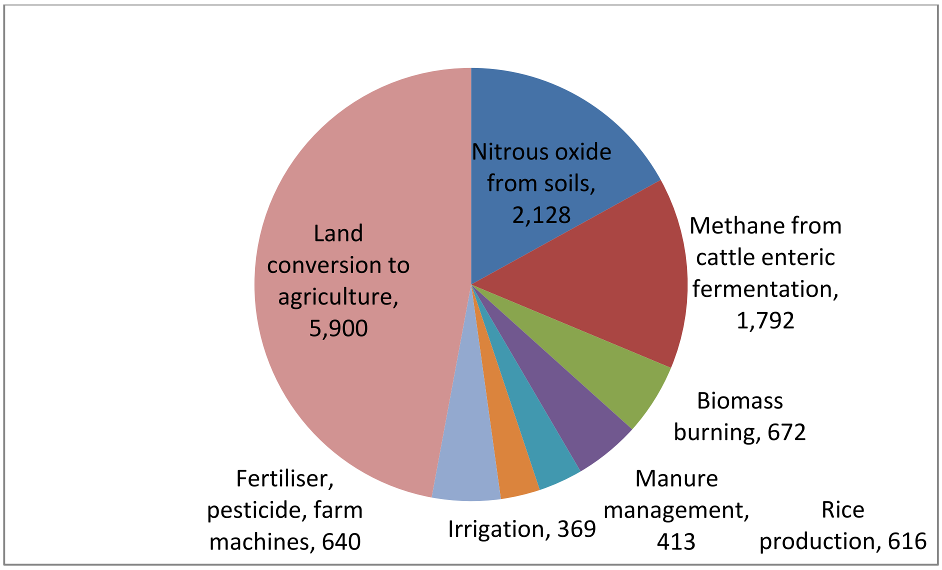
Feeding nine billion persons by 2050 will require the production of another one third to a half of current cereals output, and 43% to 85% more meat. This can be done, mainly from intensification, with yields rising by around 50%, with perhaps 10% more land used. Much of the potential for this increase appears to lie in temperate OECD countries rather than tropical developing countries.

Diet is, however, a key variable: will future generations consume animal products on the scale that many populations in the industrialised world do, or will there be the reduction in consumption per person of animal products — and vegetable oils — that many doctors would like to see on health grounds? Owing to the high demand of livestock for feed grains, meeting the needs of the future becomes much easier if future diets contained more grains, pulses, fruit and vegetables, and fewer animal products.

Current emissions from agriculture

Estimates of emissions are more common and reliable for agriculture, than for the food system as a whole. Worldwide, it is estimated that agriculture emits currently around 6.6Gt (billion tonnes) CO_2 equivalent, compared to 5.9Gt from land use conversion, most of which is for farmland — see Figure A for more details of contributions from particular sources. This compares to current total emissions of around 46Gt CO_2 equivalent: so that agriculture contributes 14% and associated land use change 13%, making a total of 27%.

Figure A: Current emissions from agriculture, M tonnes CO_2 equivalent



Source: Bellarby et al, 2008; HM Treasury, 2006.

It is not known how large emissions might be worldwide if the rest of the food system is included; although in OECD countries where large amounts of energy go into transport and processing, the addition will be large. In the UK, farm emissions are no more than 56% of all emissions in the food system, while for the EU as whole, one calculation attributed 31% of all GHG emissions to the food sector.

Business as usual will mean more farm emissions in the future, mainly in the developing world. No targets for reduced emissions exist for agriculture as a sector.

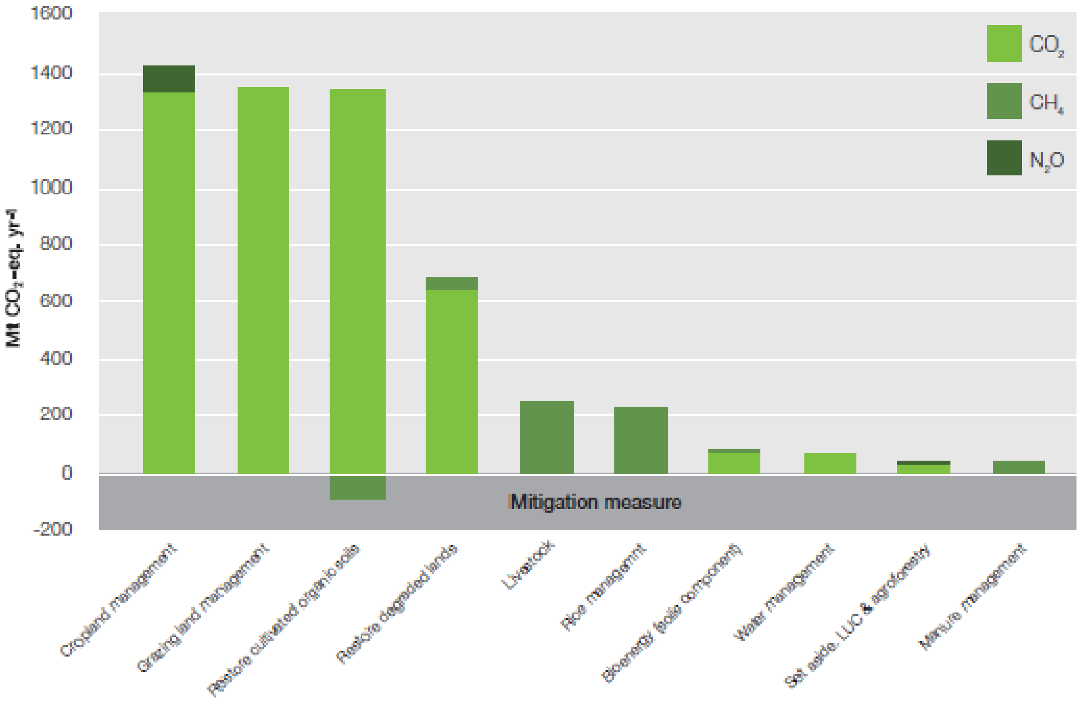
Technical Options for a Low-Emissions Agriculture

Many options for reducing net emissions exist, including:

- Crop management: replace ploughing with conservation agriculture or zero tillage; use more cover crops; conserve soil and avoid erosion; reduce pesticide use through integrated pest management; manage use of fertilisers; drain flooded rice fields when possible; adopt agro-forestry when possible to store more carbon in biomass and root zones;
- Pasture management: avoid excessive grazing;
- Restore degraded lands: allow marginal crop land to become forest, restore wetlands;
- Livestock husbandry: modify livestock diets to reduce methane emissions; increase production per head and reduce numbers of animals;
- Manage manures: use digesters to produce biogas; compost manure to reduce methane emissions; and,
- Conserve energy in production and use of industrial farm inputs: in fertiliser production, in use of machinery.

While there are ways to reduce direct emissions from farms, much of the mitigation potential arises through the potential of changed practices to sequester carbon in soils and biomass. Figure B shows the potential contributions to mitigation from changes to farming practices.

Figure B: Mitigation potential of changed agricultural practices, by 2030



Source: Bellarby et al. 2008.
Global technical mitigation potential by 2030 of each agricultural management practice showing the impacts of each practice on each GHG (taken from IPCC, 2007); Drawn from data in Smith et al., 2007.

Modelling the options

Existing models of global food production do not incorporate mitigation fully; a key difficulty being the lack of detailed and reliable estimates of emissions and mitigation possibilities. Recent global assessments of climate change and food security rely on a single modelling framework, the IIASA system, which combines agro-ecological models developed jointly with FAO, various global circulation models, and IIASA world food system model (basic linked system [BLS]).

Can nine billion be fed using sustainable methods?

In the absence of more detailed results from models, a less demanding question is whether future populations can be fed using environmentally sustainable farming. Studies reviewed were cautiously optimistic that future food needs can be met with more sustainable methods. Much depends, however, on the assumptions made about diet and how equally food supplies are distributed across populations.

There are, moreover, many experiences of more sustainable forms of farming, often pilot schemes, not all of which have been adequately documented: there may well be innovations waiting to be discovered.

Work in progress

Several groups have work in progress towards addressing these questions, including the Challenge Programme on Climate Change, Agriculture and Food Security of the CGIAR, the UK Foresight Project, Rattan Lal and colleagues at Ohio State University, and the Center for Global Trade Analysis (GTAP), Purdue led by Tom Hertel.

Conclusions

Just how nine billion will be fed in 2050 with much lower net emissions from agriculture and the food system is not known in any detail. Somewhat surprisingly, although there are studies of the needs of future food production and of the mitigation potential in agriculture, the two strands of work have not been brought together sufficiently to give more than broad indications.

Technical options exist to mitigate net emissions from agriculture: much work has been done in the last quarter century and longer to develop a menu of options; and there are many pilot programmes trialling innovations that have yet to be fully recorded or disseminated. There are thus reasons for optimism that both goals of feeding people and reducing net emissions can be met.

There is little work on the policy implications. Important choices need consideration, of which two stand out. First, it would be a lot easier to meet the twin goals if diets across the world were to converge on one that includes fewer animal products than that consumed in most OECD countries. Second, if there really is more potential to increase food production in the OECD countries, while most of the hungry are in the developing world with low purchasing power, what will be the incentive to realise this potential? Clearly there is a pressing need to define the details of a future agriculture, to assess policy implications, and begin the debates on how changes can be made.

Clearly there is a pressing need to define the details of a future agriculture, to assess policy implications, and begin the debates on how changes can be made.

Overall, the issue is hugely complex that needs to be dealt with largely at local, national and regional levels. Every community, let alone region, is unique in agroclimatic zone, land use, socio-cultural influences, food system structures, climate change impacts, levels of emissions, and potential for mitigation. Literature exists on how to deal with complexity, and on how to share and exchange knowledge and experiences between zones. If attention is paid at lower scales, the global ‘problem’ may well take care of itself.

1. Scope of the Review

By 2050 it is expected that there will be around nine billion people in the world, more than two billion more than at present. Can they be fed? And can they be fed if climate change is to be limited to two degrees of global warming or less?

The terms of reference for this literature survey was to look at existing attempts to review the options for a lower emitting agriculture at global and national levels, as well as particular case studies that compare farming systems for their emissions. Based on preliminary discussions, the review was broken down into two main sections: first to review what is known about current and future agricultural emissions, and second to review what is known about the technical options for reducing these emissions. From the start, some contextual factors were identified and these are highlighted in the Overview in the following section. The overarching purpose of this work is to assess whether we know enough to be confident that we can meet the dual goals of feeding nine billion by 2050 whilst simultaneously meeting global targets on GHG reduction. This is discussed in the final section, and recommendations for further research are made.

The scope of the review covered peer-reviewed journals and publications, and grey literature including government documents, conference papers and NGO publications. The snowballing approach was used to identify obvious first sources, and then to follow up on leads, citations and recommendations, through internet and university library resource access as well as direct communication with key individuals. Unavoidably, for the length of time available for this review, the search was most in-depth for UK and global institutional sources, and then for parts of the English speaking and industrialised world including the USA, Canada, Europe, Australia and New Zealand, with a more superficial direct search of sources in the global South. This did however mirror the quantity, relevance and/or accessibility of documents immediately available. The thematic sectors reviewed were agriculture and agri-economics, land use, climate change and food security.

Overall, no studies were found that address the core issue of feeding nine billion through a low-emissions production approach, although such studies are, according to a few sources, on their way (these are listed in Section 5).The bulk of research evidence and documentation exists on feeding the projected population, including under the impacts of climate change, and another bulk on current and future agricultural GHG emissions and approaches for their mitigation. The reasons why these have not yet been fully considered together is suggested as being fourfold:

- the sectoral and disciplinary nature of development: net emissions reduction in agriculture requires a specialist knowledge of agronomic and ecological processes that is not particularly prevalent amongst those working on food security and climate change;
- the drivers of research on emissions reduction are largely economic and technology focussed, resulting in relatively more studies on, for example, the potential and impact of biofuels than the potential for encouraging soil processes that lock up carbon;

- compared to other industries, the agricultural sector is not seen as a major emitter of GHGs; and
- agricultural mitigation approaches are perceived as being highly complex and locally specific, which makes them difficult to extrapolate to larger scales of working.

2. Overview: the Broader Picture

For the purpose of this review, it is a given that the global population will increase from 6.8 billion today to 9.1 billion by 2050, that is, a 34% rise. Urban populations will increase from 49% of this total to 70%, and nearly all growth will occur in less industrialised countries (FAO, 2009). Within this, we – have to - assume that no natural or man-made phenomena between now and 2050 will significantly affect population numbers. It is also a given that the climate is fluctuating, whether or not this be significantly man-made, or whether over the short, medium or long term. During this century our food production systems need to adapt to this change, just as traditional production systems adapted — or not – to previous climate fluctuations. The third given is that the population will need to feed itself, although the precise socio-economic and agroclimatic circumstances under which this will happen are unknown.

Several other key factors are not givens, and place the review in context. These are interrelated. The first factor concerns the way that the discourse is couched. Debate invariably attempts to solve the 'problem' of how to feed nine billion. This rather top-down and paternalistic perspective may be turned on its head by electing a more empowering enquiry into how communities, cities and whole countries and regions can be enabled to feed themselves? Such an enquiry would imply consideration of the food sovereignty approach – that is, the right of peoples to define their own food, agriculture, livestock and fisheries systems - and this would have implications for developing the methodology, means and decision-making structures over how to reduce emissions and at what scales. Such an approach would be concerned and capable to address distribution and equity impacts of changes in land use patterns or production systems, as well as impacts on farmers (especially in less industrialised regions), gender implications and so on.

The second factor concerns agriculture in relation to the food system. If the food system is included in calculations, then figures of GHG emissions and reduction potential become far more significant. In fact, specific agricultural systems and products are inseparable from elements of the food system; for example, reducing emissions of industrial maize, soya or palm oil production may have implications for the food processing industry on which it is based. Conversely, a change in the food supply chain also affects production: a re-localisation of markets, for example, may induce a broader diversity of crops but smaller volumes per crop being grown. This review therefore includes basic literature on food systems' emissions and reduction potential.

The third key factor concerns the productivist approach to food security. Feeding nine billion is not simply a question of increasing food availability from current levels in proportion with population growth. Food security is equally concerned with, and dependent on, accessibility and adequacy, and this means that global projections are inadequate to ensure food security at the level of the human being. We know that there is already a global food surplus, yet over 1 billion go hungry (FAO, 2009), whilst 1.6 billion are currently overweight and 400 million obese (WHO, 2006). Overall, 2.7 million deaths annually are attributable to low fruit and vegetable intake; being the cause of 19% of gastrointestinal cancer, 31% of ischemic heart disease and 11% of strokes (WHO, 2003). This dietary-related ill-health is not included in food costs, but instead is paid for by governments and society. In 1996, for example, these health costs amounted to $81–117 per ha in Germany and $343 per ha in the UK (Pretty et al, 2000). Indeed, in 2002, the FAO estimated that achieving the goal of halving the number of hungry people would generate global annual incremental benefits of $120 billion during the period up to 2010 (FAO, 2009). Thus, the composition (quality) of available food is just as important as the quantity and this should be factored into forecasts. Conversely, attempts to reduce agricultural emissions may affect the types and quantities of foods available, as well as the locations where they are produced thus affecting accessibility. Distribution and equity impacts are also important. Over-consumption of, for example, an unlimited amount of livestock products, should not necessarily be a development goal nor one that is factored into future food forecasting. Further, evidence shows that taking a singular focus on maximising yields and volumes at the expense of other agro-ecological or socio-economic factors, tends to put land, agrobiodiversity and smallholders out of production over the longer term, in this sense negating any short-term gains (ISRIC, 2010; Wright, 2008; Bennett & Carpenter, 2005) Finally, we know that the food system is leaky: between 30-40% of food is wasted. In less industrialised countries, this waste is largely due to poor pre- and post- harvest handling and storage, whilst in industrialised, the losses are largely post-retail (Nellemann et al, 2009; RSA, 2009; Stuart, 2009; Cabinet Office, 2008; WRAP, 2008). In the UK, for example, 20 million tonnes of food is wasted, equivalent in value to half of the food import needs for the whole of Africa (Mesure, 2008). More cost effective over the long term would be to prioritise reducing these inefficiencies, net losses and wastage, and to factor these efforts into future food forecasting, than continue at deleterious attempts to force productivity at the expense of sustainability and of the bigger picture. Therefore, for this review, the logic behind the current production targets for feeding nine billion by 2050 is under question, and sustainable mitigation strategies that may not necessarily be the highest-yielding are considered favourably in the review. The fourth and final key contextual factor for this review concerns the focus on reducing emissions. This focus is one side of the coin, albeit the more popular one as it opens the way for the development of more technologies. The other, less heralded but equally important, side of the coin is carbon sequestration and carbon capture, the technology for which has existed for millennia. Both sides of the coin are reviewed here under the umbrella of emissions mitigation. The third side of the coin - if there was one - is that the emissions targets and available resources for mitigation are constantly changing under the influence of climate change. For example, the IPCC estimates that crop yields could drop by 20-40% in less industrialised regions if temperatures rise by more than 2^{o}C (Pachauri & Reisinger, 2007). This and the previous factors indicate that, as well as identifying the technologies to reduce emissions in the farming and food system, equally important will be a host of other factors including trade-offs, methodologies for problem solving, and scales of working.

3. Food Production in Relation to Current and Future Emissions

3.1 Feeding nine billion – how much more food do we need, and can this be achieved with the land available?

Food projections to feed nine billion by 2050

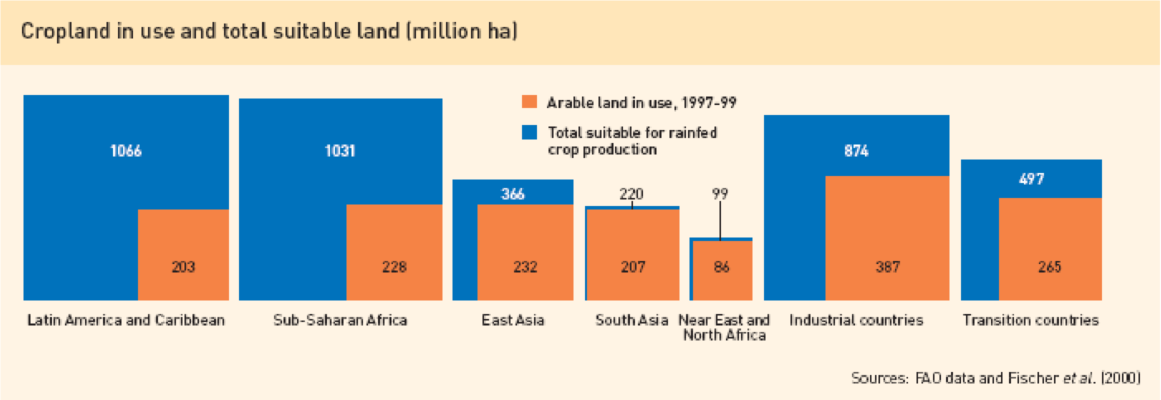
The FAO's recent report 'How to Feed the World in 2050' provides a useful backdrop from which to look at emissions. A result of the Meeting of Experts in Rome, June 2009, the report provides up-to-date thinking on predicted food needs and land availability to 2050. Several working papers formed the basis for this report and for the subsequent High Level Expert Forum in Rome, October 2009. The overall conclusion is that it would be possible to produce sufficient food to feed nine billion by 2050, assuming certain conditions were met. Included in these conditions were discussion on the adaptation to climate change and a brief mention of carbon sequestration.

Background papers to the Meeting of Experts include those by Bruinsma (2009) and Fischer (2009), which discuss the natural resource and climate change implications of the latest FAO food and agriculture baseline projections to 2050. These form a consensus that food and feed production need to rise by 70%, with cereals rising 33% to 3 billion tonnes and meat production rising by 43% to 470 million tonnes. The reason for these projected rises is not only population growth; the aim is also to raise average food consumption to 3130 kcal per person per day by 2050 in order to eliminate hunger. Other estimates of increases in food production are higher: Rosegrant et al, (2008) suggest a rise in cereals by 50% and in meat by 85%, and the Royal Society report 'Reaping the Benefits' (2009) suggests a total increase of between 50–100%. There is some dissent: Keyzer et al (2005) argue that competition over crop by-products and residues will make it impossible to feed enough livestock to meet demand. There is no data on emissions associated with this projected growth.

Sustainable intensification and land availability

Globally, 90% of the growth in crop production would come from intensification, in particular through higher yields and increased cropping intensity (IAASTD, 2009). Average cereal yield would rise by 2050 to reach some 4.3 t/ha, up from 3.2 t/ha at present. Bruinsma (2009) sees considerable potential to raise crop yields (even with existing technology) based on the difference between agro-ecologically attainable and actual yields that could be exploited. That the natural resource base should be adequate to meet the future demand at global level is one of the conclusions from the Millennium Development Assessment (Bennett & Carpenter, 2005). This conclusion is dependent on the assumption that the current widespread degradation of ecosystems services (15 out of the 24 examined in the assessment) is halted and land use practices made more sustainable. Bruinsma's Global Agro-Ecological Zone study shows that there are still ample land resources with some potential for crop production, and that this is concentrated in a few countries in Latin America and Sub-Saharan Africa. In support of this, the FAO Report calculates that the area of arable land could be expanded on average by 5% or 70 million hectares, almost all of that in less industrialised countries. The FAO's more intensive scenario, an expansion of land by 9% and of yields by 54%, is in line with the work of the International Institute of Applied Systems Analysis (IIASA) that suggests a growth of cropland area of between 6 and 12% to 2050. However, Kahn & Zaks (2009) discuss an alternative model developed by researchers at the Potsdam Institute that reallocates land uses to the most productive regions of the world. These two regions, Western Europe and Eastern United States, are termed the "Global Agricultural Commons", and are seen as the least affected by climate change and therefore the areas holding most productive potential over the long term. According to the authors' estimates, by concentrating production on these sites, the growing population could be fed.

Figure 1. Cropland in use and total suitable land (million ha)



Source: FAO, 2002

Other major factors that will affect food production to 2050 have not been discussed; these include phosphorus and water supplies. In the case of phosphorus, for example, supplies may run out within 40 years and this would produce a yield decline of approximately 30%. It is unclear whether the above forecasts take this into account.

The impact of climate change on production

There is also general consensus on the overall negative impact of climate change on agriculture, including from IFPRI's recent report 'Climate Change: Impact on Agriculture and Costs of Adaptation' that presents research results quantifying the climate change impacts and consequences for food security (Nelson et al, 2009), the FAO's 'Climate Change and Food Security, A Framework Document' that explores the multiple effects that global warming and climate change could have on food systems and food security, and suggests strategies for mitigating and adapting to climate change (FAO, 2008), and the World Bank Discussion Paper on climate change response (Tubiello et al, 2008) that analyses the impacts of climate change on food supplies and food security. In Cline's 'Global Warming and Agriculture: Impact Estimates by Country' (2007), the author provides a comprehensive evaluation of whether aggregate global agricultural impact might be negative or positive by within this century. Cline reaches two conclusions: first, that global warming will have a modest negative impact on global agriculture, but that this will be more severe if the expected carbon fertilisation benefits (the enhancement of yields in a carbon-rich environment) do not materialise. Second, that the impact will be least favourable in less industrialised countries, the most severe losses occurring in Africa, Latin America and India.

Studies that model the impacts of climate change on food security concur that the world can feed itself under IPCC Special Report on Emissions Scenarios (SRES) for the rest of the century, mainly through higher production in industrialised countries compensating for losses in less industrialised countries (Parry et al, 2004). Various other reviews and papers come out with similar results. The Special Section of the journal Science, February 2010, is dedicated to 'Feeding the Future'. This section examines the obstacles to achieving global food security and some promising solutions. Perhaps the most relevant contribution is the paper of Godfray et al. that concludes that we have perhaps 40 years to radically transform agriculture, work out how to grow more food without exacerbating environmental problems, and simultaneously cope with climate change. Another author, Barrett, discusses the continued difficulties in measuring food security. Ejeta, discussing Africa's green revolution, notes that many African nations have set a target for science-based annual productivity growth of greater than 6% by 2015.

Datasets and dietary omissions

Contributing to data on food predictions is the FAO's report 'World Agriculture: Towards 2015/2030'. Production data for all studies draw heavily from the FAOSTAT database (http://faostat.fao.org) that provides time-series and cross sectional data relating to food and agriculture for around 200 countries, including food balance sheets of countries' food supplies, as well as the quantities, areas and yields of the highest value 20 crops for each country – chiefly cereals, oil crops and sugar crops. A national version of FAOSTAT is being developed, and these databases could also be used in analyses of emissions reductions. It does not report on projections for fodder crops, and nor, as Bruinsma notes (2009), does this data explicitly account for land use changes due to climate change.

A point worth noting in the light of awareness of health and dietary implications is that all these projections focus on two food components: cereals and livestock. In fact, the food system currently depends on 12 animal species to provide 90% of animal protein consumed globally, and 4 crop species to provide 50% of the plant-based calories (Bennett & Carpenter, 2005). Compare this with standard dietary recommendations that promote an intake of at least 33% of fruit and vegetables, with another 33% coming from carbohydrates (cereals but also roots and tubers), and the other 33% comprising limited amounts of protein, dairy, fats and sugars (FSA, 2001). The cause of this omission is at least partly because fruit and vegetables are not treated as commodity crops and do not significantly feature in the FAOSTATS database. The FAO Report 'How to Feed the World' does point out that food preferences are also predicted to change, with shares of grains and other staples declining and those of vegetables, fruits meat, dairy and fish increasing. Srinivasan et al (2006) looked at the implications for production if everyone ate a healthy diet. Based on WHO/FAO nutritional guidelines, the study concluded that this would require substantial changes in production and consumption, to reduce meat, vegetable oils, eggs and dairy, and increase more cereal-based products, pulses, fruit and vegetables. The authors concluded that only a small rise on overall production requirements would be necessary to feed the current population, since the increase in human consumption of grains would be almost entirely offset by the reduction in demand for feed cereals. There is a case for revising global and national calculations on food demand to recognise the importance of this broader range of foodstuffs.

3.2 Current and future emissions for agriculture and the food system

Key issues and literature on agricultural emissions

Over the last ten years or so, an exhaustive range of literature has built up on the impacts of climate change on agriculture, at all levels from global to community case studies, and to a lesser extent a body of evidence on agricultural emissions. This evidence exists more for industrialised countries than for less industrialised. Within this, the IPPC provides a solid overview of global, regional and national trends that are updated on a regular basis. These come in the form of Assessment Reports of scientific, technical and socio-economic information relevant for the understanding of climate change, potential impacts of climate change and options for mitigation and adaptation, and include reviews of current knowledge. Four Assessment Reports have been completed in 1990, 1995, 2001 and 2007. A fifth is underway. The IPCC also publishes Guidelines for National Greenhouse Gas Inventories, which include emissions from the “agriculture, forestry and land use sector”. From the United States, the Environmental Protection Agency publishes ‘Global Anthropogenic non-CO2 Greenhouse Gas Emissions, 1990-2020’ (2006). This report provides historical and projected estimates of GHG emissions for over ninety countries and eight regions.

Agricultural emissions vary depending on land use and the way that the land is managed, and quantifying emissions has to be done at the level of individual farming practices rather than by characterising farms (or regions) as, for example, more or less intensive. This is because of the complex interactions between practices and effects, as well as the lack of statistics on land use intensity and the fact that both intensive and extensive subsystems are often practiced on the same farm. When samples are taken, they often provide different results because soil carbon is characterised by spatial, seasonal and annual variation, and sampling itself is intensive and costly (Bellarby et al, 2009; Garnaut, 2008; HM Treasury, 2006).

Further, in quantifying emissions, authors may focus on different aspects of the whole production system. For example, authors with an interest in biological processes (such as Smith et al, 2007) tend to focus on modelling the biologically-generated emissions from on-farm, such as that from decomposition and decay. Other authors recognise energy emissions: the IAASTD report (2009) highlights the relationship between food and energy systems and the correlation between energy inputs and yields. Although agricultural production represents only a small part of global energy consumption, the food supply chain uses significantly more. In the EU, for example, 7% of total energy consumption is attributed to the food chain (Ramirez-Ramirez, 2005), and within this, 45% is consumed by food processing industries, 25% by agriculture, 10-15% by transport of food and fodder, and 5-10% for each of fertiliser manufacturing and transport of agricultural products. Thus, calculations may include the embedded emissions from the production of nitrogen fertiliser and pesticides, and/or the energy emissions from farm machinery and irrigation equipment (for example, Bellarby et al, 2009). Lal (2004) in his comprehensive paper has synthesised the available information on energy use in farm operations and its conversion into carbon equivalent, and compared intensive and extensive practices. In fact, Lal divides agricultural practices up into primary, secondary and tertiary sources of carbon. Primary sources are mobile operations, such as tilling or harvesting, or stationary operations such as pumping water or grain drying. Secondary sources are manufacturing, packaging and storing of fertilisers and pesticides. Tertiary sources are the acquisition of raw materials and construction of equipment and farm buildings. A few studies, chiefly those encountered from the UK, Audsley et al (2010), Cabinet Office (2008) and Garnett (2008), recognise and consider the production system within the broader food system, and quantify other embedded emissions, frequently through life cycle analyses.

In the literature reviewed and especially those that refer to modelling, two grey areas comprise land clearance for agriculture, and agroforestry. Land use clearance is often treated separately, especially because of its recent association with the production of biofuels that are not classified within agricultural statistics. However, land clearance may also be associated with livestock grazing and the production of feedstock such as soy. Agroforestry, that is, forestry that is being managed to provide an ecosystem food service, is also excluded from agricultural emissions (and sequestration) analyses, and this may be because of the perception of the authors on the provenance of food. Two other, interrelated issues that have not been a focus of this review but do feature heavily in the literature are biofuels and water management. Biofuels in particular, though not a food, have been a major focus of work because of their potential commercial importance. Globally, sustainable food production takes priority for land use on ethical grounds, as there are other means for producing renewable energies. On a local, community level, however, this prioritisation may differ. Aquaculture, whilst an important contributor to GHG emissions and mitigation, is also not included. It should also be noted that agriculture produces more than food, but that this study is concerned with feeding the population and so non-food products are not considered.

Along with, and partly based on, the work of the IPCC, a handful of key documents review the evidence for current and future emissions (as well as for strategies to mitigate and/or adapt to climate change). For the UK, one of the first and most comprehensive reviews on future emissions was the Stern Review on the Economics of Climate Change, in 2006, that set out to assess the nature of the economic challenges of climate change and how they can be met both in the UK and globally. Similar to the UK's Stern Review, Garnaut (2008) undertook a similar assessment for the Australian Government, although in less detail and focussing on one country rather than with broader global implications. A more recent, and possibly the most succinct review is 'Cool Farming, Climate Impacts of Agriculture and Mitigation Potential', by Bellarby et al (2008). Funded by Greenpeace, the authors make a comprehensive review of literature on the sources of GHG emissions in agriculture, converting data into uniform measurements for ease of comparison. They analyse current and projected global emissions, as well as indirect emissions from farm operations, the production of agrochemicals (including projections on intensification) and various forms of land use change. The report highlights livestock, and also compares intensive versus non-intensive agricultural practices. Alongside this, WWF and the Food and Climate Research Network (FCRN) commissioned a report to assess GHG emissions from the UK food system and the scope for reduction by 2050. “How Low Can We Go” (Audsley et al, 2010), develops and analyses a set of scenarios that explore how GHG emissions from the UK food system may be reduced by 70% by the year 2050. This report looks at emissions not only from the UK food system but also those from international supply chains and systems. However, estimates are based on the current UK population, so as not to confuse the effectiveness of measures with population growth.

Main agricultural emissions and their sources

Agriculture releases three main types of GHG into the atmosphere: carbon dioxide (CO_2), methane (CH^4) and nitrous oxide (N_20). There is consistent agreement over global emissions estimates, although the different means of expression can make it somewhat confusing. Emissions of nitrous oxide and methane are usually expressed as the equivalent units of carbon dioxide in terms of their global warming potential in 100 years: nitrous oxide has 296 times the warming potential of carbon dioxide, and methane 23 times, as both are more efficient in trapping heat (Bellarby et al, 2008; US-EPA, 2007).

Box 1: Greenhouse gas emissions in agriculture: where do they come from?

Carbon dioxide: Released largely from microbial decay or burning of plant litter and soil organic matter. Also associated with land clearance of native vegetation for agricultural usage. Plus farm machinery, agrochemical production and irrigation usage.
Methane: Released when organic materials decompose in oxygen-deprived conditions, notably from fermentative digestion (enteric fermentation) by ruminant livestock (contributes 32% of total non-CO_2ag-emissions not including land use change), stored manures and wet rice. Plus farm machinery, agrochemical production and irrigation usage.
Nitrous oxide: Released by the microbial transformation of nitrogen in soils and applied through nitrogen fertiliser and manures, often enhanced where available nitrogen exceeds plant requirements especially under wet conditions (contributes 38% of total non-CO_2ag-emissions). Also associated with biomass burning and rice production. Plus farm machinery, agrochemical production and irrigation usage. Agricultural systems produce about a quarter of global N_2O emissions.
(Source: Bellarby et al, 2008; IPPC, 2007; Smith et al, 2007; Oenema et al, 2005; Janzen, 2004; Smith, 2004; Smith & Conen, 2004; Mosier et al, 1998)

Most of the literature bases its analyses on IPCC assessments (most recently, the IPCC Fourth Assessment Report, Working Group III, 2007), such as FAO (2009), Bellarby et al (2008), Smith et al (2007), HM Treasury (2006), and concurs that agriculture currently contributes between 10–14% of global anthropogenic GHG emissions. According to the World Bank Development Report (2008), however, it accounts for up to 30% of GHG emissions, and to Weyant et al, in the Special Edition of the Energy Journal (2006), 25%. This divergence may be due to the factoring in of different segments of the whole production system. For example, Bellarby et al explain that if estimates include agricultural land use change (17%), agrochemical production and distribution (1.4%), and farm operations (1.8%), then the total global contribution of agriculture considering all direct and indirect emissions is between 16.8 and 32.2%. Paustian et al (2006) also conclude emissions of 30% if land use change is included with agriculture.

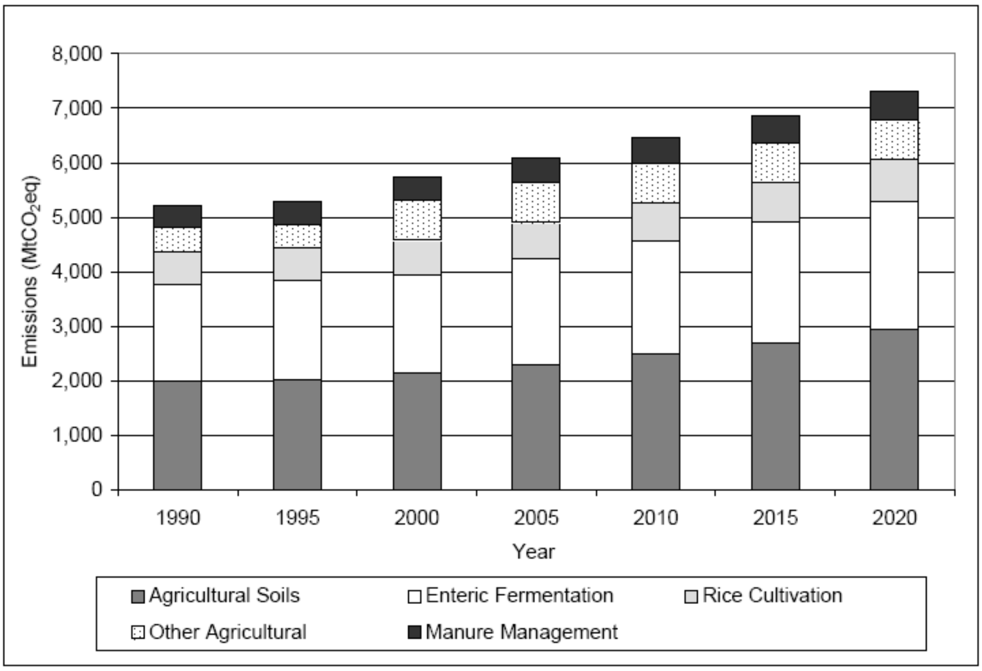
Table 1.Sources of GHG emissions by agricultural land use and main activity (Million tonnes CO2 equivalent (global total), and percentage

Source	**Mt C0^2 eq.**	**%**
Nitrous oxide from soils	2,128	33
Methane from cattle enteric fermentation	1,792	27
Biomass burning	672	10
Rice production	616	9
Manure management	413	7
Fertiliser production	410	6
Irrigation	369	5
Farm machinery	158	2
Pesticide production	72	1
Land conversion to agriculture	5,900	-

Source: Bellarby et al, 2008; HM Treasury, 2006.

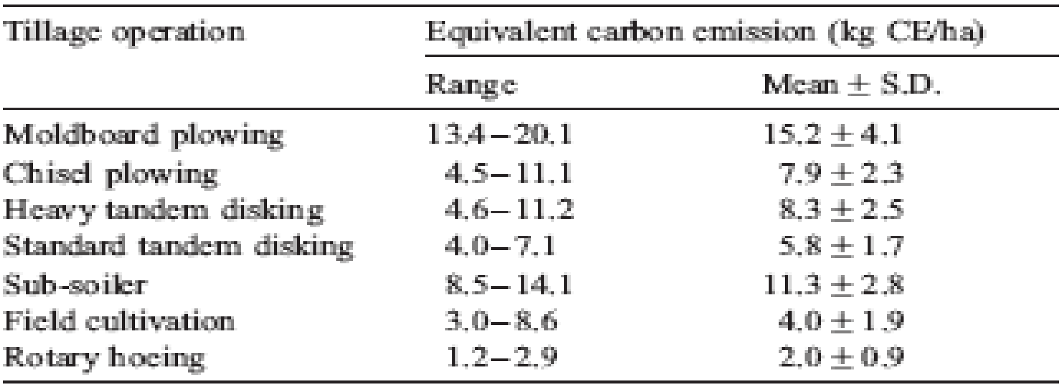
Compared with direct agricultural activities, land use clearance for agriculture releases approximately 5.9 Pg CO^2 equivalent per year (IPCC, 2001). Deforestation in general is responsible for up to 18% of global GHG emissions (Bennett & Carpenter, 2005).

Figure 2. Total emissions from the agricultural sector by source (MtCO$_2$eq)



Source: US-EPA, 2007

Figure 3. Estimates of carbon emissions for a range of tillage operations



Tillage operation	Equivalent carbon emission (kg CE/ha)	
	Range	Mean ± S.D.
Moldboard plowing	13.4–20.1	15.2 ± 4.1
Chisel plowing	4.5–11.1	7.9 ± 2.3
Heavy tandem disking	4.6–11.2	8.3 ± 2.5
Standard tandem disking	4.0–7.1	5.8 ± 1.7
Sub-soiler	8.5–14.1	11.3 ± 2.8
Field cultivation	3.0–8.6	4.0 ± 1.9
Rotary hoeing	1.2–2.9	2.0 ± 0.9

Source: Lal, 2002

Regional patterns of agricultural emissions

Less industrialised and countries in-transition show the most rapid increase in emissions, of 35% between 1990 to 1995, and are currently responsible for three-quarters of global agricultural emissions. Meanwhile, industrialised regions collectively show a decrease of 12%. In the UK, the agricultural sector contributes 38% of all UK methane emissions and 67% of nitrous oxide emissions (DEFRA, 2009). For the EU it has been estimated that agriculture contributed up to 9% of the EU-

15’s GHG emissions in 2005 (EEA, 2007). In the USA in 2007, the agriculture sector was responsible for 6% of the U.S. total GHG emissions. In Australia, enteric fermentation emissions from livestock accounted for 67% of agricultural emissions (Garnaut, 2007), while in New Zealand, agriculture contributes half the country’s emissions, owing to its intensive dairy industry (Greenpeace, 2008). These figures do not include land use change.

By activity, nitrous oxide from soils is the main source of GHG from industrialised nations, Africa and most of Asia. In Central and South America, Eastern Europe, Central Asia and the Pacific, enteric fermentation is the dominant source, owing to the large livestock populations in these regions (Bellarby, 2008; US-EPA, 2006, FAO, 2002). Emissions from rice production and biomass burning come almost exclusively from less industrialised countries – the former activity largely in South and East Asia and the latter from Africa and South America. Emissions from manure management has a more even geographic spread.

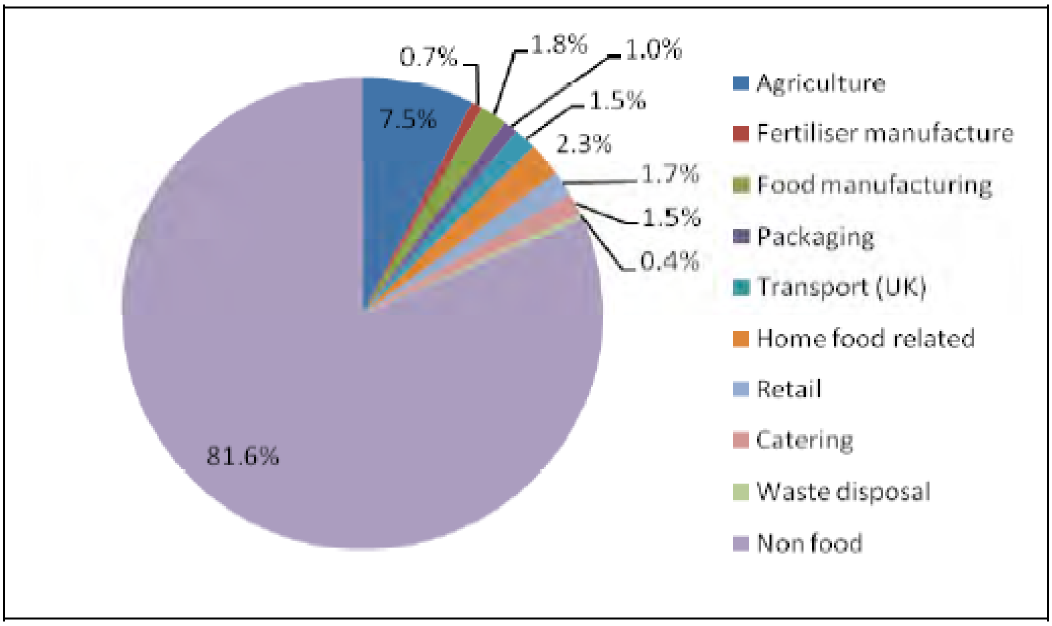
Food systems emissions

Emissions in the food system or food chain are analysed from the perspective of consumption emissions, frequently through assessment by life cycle analysis. These assessments are clearly more relevant for industrialised countries than less-industrialised. No data could be found on attempts to quantify GHG emissions resulting from global food consumption and the global food system. Of the UK’s total GHG consumption emissions, its food system contributes between 18–20% (Audsley et al, 2009). The supply of food and drink for UK consumption results in emissions of 152Mt CO^2, and a further 101 Mt CO^2 if land use change is included. Animal products account for 58% of direct food system emissions, and two thirds of food production emissions arise in the UK (the remainder arising from production overseas to meet UK consumption demand). Agricultural production contributes 56% of total UK food system emissions.

Also in the UK, the Food and Climate Research Network (FCRN) has undertaken a series of studies on different aspects of food, their carbon emissions and ways to reduce these, using a life cycle approach. These studies cover alcoholic drinks, fruit and vegetables, meat dairy and other livestock products, and food refrigeration (Garnett, 2008; 2007; 2007a; 2006; 2006a). ‘Cooking up a Storm: Greenhouse Gas Emission and Our Changing Climate’ (Garnett, 2008) provides a useful analysis of the different kinds of emissions and different ways of measuring them, as well as an analysis of healthy diets and implications for GHG. One striking fact is that the UK cold chain is responsible for approximately 15% of total food chain emissions. Food wastage is also analysed: at the household level alone, 18 million tonnes CO_2 is wasted (as emissions from the food production and supply chain), equivalent to 2% of the UK’s production-related emissions (WRAP, 2008).

At a European level, an EIPRO study (2006) calculated agricultural emissions through to consumption using environmental input-output analysis. The food sector in its entirety accounts for around 31% of the EU-25’s GHG emissions. This report also reviews life cycle studies. From further afield, Saunders & Barber (2007) compared the GHG footprints of British and New Zealand dairy industries, and found that British emissions were 34% higher and 30% more on a per ha basis than the New Zealand system, even allowing for the shipping emissions of New Zealand's export-oriented system.

Figure 4. Food and its contribution to UK GHG emissions – a production oriented perspective



Source: Garnett, 2008

Future emissions if business-as-usual

When the Stern Review was compiled, there were no available estimates of agricultural emissions by 2050. More recent data on future emissions tends to look to a timescale to 2020 or 2030 and are based on current trends in agricultural intensification and dietary changes. Few consider the scenario of a low-emissions agriculture. The main literature sources are Bellarby et al, Smith et al, the IPPC, FAO and US-EPA, and also Mosier &Kroeze (2000). The main driver behind emissions growth is, crudely, income, and indirectly population growth, an increasing demand for meat (livestock numbers are expected to double by 2020) and increased productivity that requires more production and food chain resources (HM Treasury, 2006).

Agricultural nitrous oxide emissions will increase by 35–60% until 2030, and methane by 60%, driven by the increase in use of nitrogen fertiliser and increased livestock production. This is a more rapid increase than the 17% experienced between 1990 and 2005 (FAO, 2002). US-EPA predicts a 16% increase in methane emissions between 2005 and 2020, based on increases in irrigated rice production. In terms of land use change, Houghton (2005) calculates that under a 'business-as-usual' scenario, emissions will remain at round 7.5 Gt CO^2/yr until 2012, reducing to 5 Gt CO^2/yr by 2050 (this model assumes that countries will halt deforestation when only 15% of their forests remain).

By region, and according to the US-EPA, the Middle East, North Africa, and SSA have the highest projected growth in overall emissions, of 95% increase between 1990 and 2020; owing to the expected increase in intensive production and potential development of industrialised farming. East Asia will have the highest increase in emissions from enteric fermentation and manure, of 153% and 6% respectively. North America and the Pacific are the only industrialised regions with a forecasted increase in GHG emissions from 1990 to 2020, of 18% and 21% respectively. This increase is driven by emissions from manure and from the soil. Western Europe, on the other hand, is the only region where GHG emissions from agriculture are projected to decline by 2020, mainly due to policy interventions.

Emissions reduction targets

In 'A Copenhagen Prognosis: Towards a Safe Climate Future: A Synthesis of the Science of Climate Change, Environment and Development', Kartha et al (2009) warn that if we are to have a good (75%) chance for warming to stay below 2°C, global GHG emissions would nearly certainly need to decline extremely rapidly after 2015, and reach essentially zero by mid-century.

There are few emissions targets specifically for agriculture, partly since the importance of the sector as a source of GHG has been under-appreciated, and partly since mitigation is seen as more complicated in agriculture compared to other activities, such as power generation. Overall targets for reducing GHG emissions are unclear and especially after the outcome of the Copenhagen Summit. The most significant international agreement remains the Kyoto Protocol, signed and ratified by the majority of countries with the exception of the United States. Rich nation signatories (known as Annex 1 countries), who collectively account for approximately 60% of global emissions, were committed to reduce their emissions by 5% (on average) from 1990 levels by 2008–2012, although country-specific reductions varied. Less industrialised countries were not obliged to reduce their emissions, although this is now questionable for the emerging economies of China and India. Using the contraction and convergence approach – a burden-sharing scheme based on per capita emissions rights, some countries require greater reductions than others. Japan, for example, will have to reduce its GHG emissions by 82% compared to those in 1990 (Matsuoka, 2005). (A more appropriate burden sharing approach is the Greenhouse Development Rights approach (http://gdrights.org) that distributes the burden on the basis of common but differentiated responsibility for emissions and respective capability for mitigation.)

The EU (with 27 members) counted as one signatory, and was committed as a whole to reducing its emissions by 8% on 1990 levels. Individual EU member states have individual targets within this overall objective, the UK's being to reduce its GHG emissions by 12.5% by2008–2012.At an EU level, in January 2008, the European Commission announced a package of legislation aimed at delivering a 20% cut in GHG emissions by 2020. A key component of this will be the EU Emissions Trading Scheme (Bellarsby et al, 2009).

In the UK, the Climate Change Act 2008 made the UK the first country in the world to have a legally binding, long-term framework to cut carbon emissions. This Act places on the UK Government a legal requirement to ensure that the country reduces its CO_2 emissions by 80% by 2050, with an immediate target of between 34% by 2020 (and 42% if a global deal on CC is reached). The government has set an aim for GHG emissions from farming in England to be cut by 3 Mt CO_2eq a year between 2009 and 2020 (DEFRA, 2009) – a reduction of 6% on what emissions would otherwise have been. Scotland's targets are a little clearer and more stringent.

4. Technical Options for a Low-Emissions Agriculture

Key issues and literature on agricultural mitigation options

The Stern Review notes that compared to other sectors, relatively little work has been done on how to cut emissions from the agricultural sector. A few authors, such as Pretty at the University of Essex, have nevertheless been working on this issue for at least a decade (e.g. Pretty et al, 2002), and the principles and main approaches for reducing emissions in agriculture are now relatively well documented, especially driven by the emergence of the carbon credit market in the early 1990s. As with the identification of GHG emissions from agriculture, reductions can be seen as those purely relating to production activities, or can include the energy systems used on-farm, the embedded energy used to manufacture products brought on-farm, or the food chain into which the production system is itself embedded. Then, as well as reducing emissions, the other side of the coin is carbon capture, which is what plants and microorganisms do, and production systems can be designed to maximise this process. The majority of authors recognise that a major solution to the issue of climate change lies in shifting farming practices to become providers of large-scale carbon sinks. The IPCC (2007) predicts that climate change will aggravate the effects on crops of stresses such as heat, drought, salinity and submergence in water. As a reaction to this, there is a plethora of literature on ways to adapt agriculture to climate change. For example, The Royal Society report (2009) emphasises the importance of developing improved crop germplasm and improved crop practices in order to adapt to these changing circumstances. Whilst adaptation is a pragmatic response, it does not necessarily solve the challenge and may even exacerbate it. The mentality of adaptation may mean that opportunities for going further with mitigatory actions are overlooked. For example, developing and introducing drought-tolerant germplasm actually supports the maintenance of a dryland environment, whereas mitigatory actions could be taken to reverse a productive environment's decline into a long term drought situation by, for example, harvesting and storing annual rainwater, and increasing the spread of ground cover and perennials. Nevertheless, some agricultural approaches considered as adapting to climate change should have a beneficial effect on mitigation, simply because they will increase plant growth that will, in turn, increase carbon capture.

The latest IPCC Report (Smith et al, 2007) provides figures for the mitigation potential in each climatic region (cool-dry, cool-moist, warm-dry, warm-moist) for livestock and non-livestock activities. It does not address the use of agricultural inputs and machinery. Some activities only impact one type of greenhouse gas, and others several. There is also variability across climates. As such, there is no universally applicable list of mitigation practices, but each practice needs to be evaluated for individual agricultural systems according to the specific climate, edaphic, social, historical land use and management context. The IPCC have also published a voluminous report on Carbon Dioxide Capture and Storage (Metz et al, 2005), though this has surprisingly little reference to biological means of carbon capture.

GHG mitigation potential and techniques

The global technical potential for mitigating GHG emissions is of 6 PG CO^2-eq per year by 2030 (Smith et al, 2007). This is equivalent to offsetting all current agricultural emissions (IPCC, 2007), and a lower figure is therefore more realistic. The Stern Review suggests a total economic abatement potential by agriculture of at least 5.5 $GtCO^2$ in 2050, through afforestation, agroforestry, and the halting of deforestation. The FAO (2009) has a similar forecast, of mitigating between 5.5 and 6 GT of CO^2 per year.

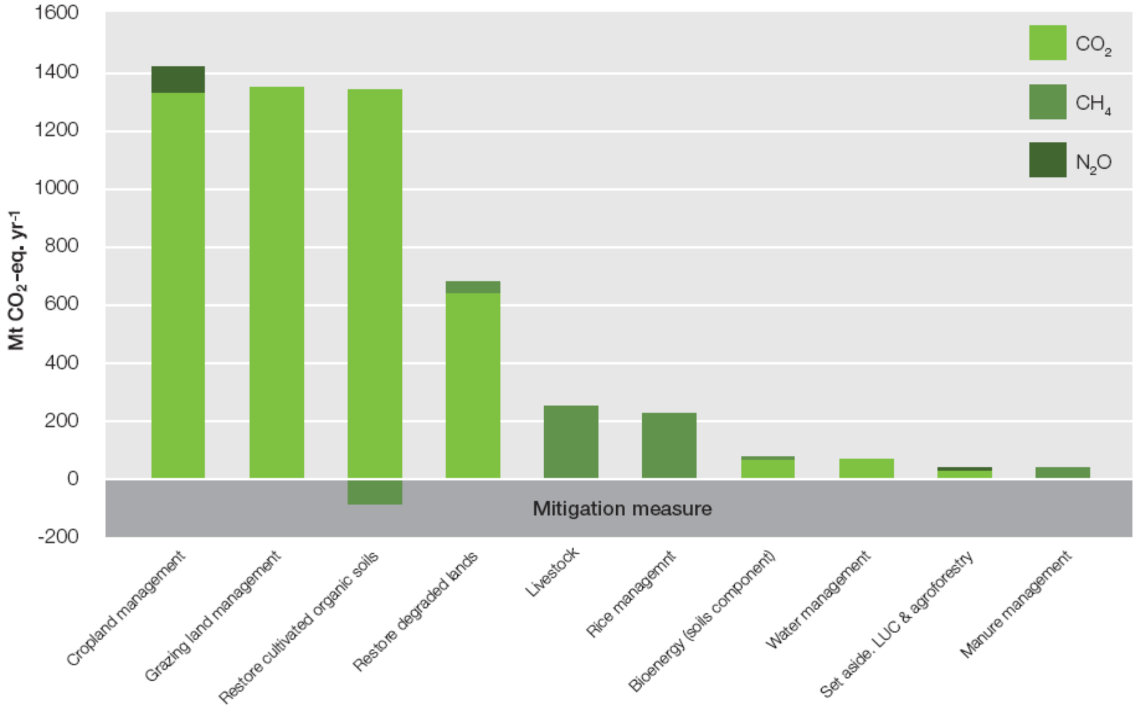
Table 2.Potential for GHG mitigation in European agriculture compared to baseline (Mt CO2-eq)

Indicator	Historical			Baseline		Mitigation	
	1990	2000	2010	2020	2050	2020	**2050**
Agriculture	**579**	**491**	**482**	**462**	**408**	**363**	**213**

Source: Heaps et al, 2009

The main approaches for carbon mitigation are outlined below, drawing from Pretty, 2008, and Bellarby et al, 2009. An early seminal work by Cole et al (1997) who analysed mitigation options in agriculture, estimated that of the total potential emissions reductions, approximately 32% could result from reduction in CO_2 emissions, 42% of carbon could be offset by (the carbon captured by) biofuel production on 15% of existing croplands, 16% from reduced CH_4 emissions and 10% from reduced emissions of N_2O. Robertson & Grace (2004), Mosier et al, (2004), and Palm et al (2004) compare temperate and tropical ecosystems and differences and similarities in GHG behaviour, and look at the advantages of agroforestry systems. The US EPA report and much of the other literature on carbon emissions also covers adaptation, reduction and/or mitigation strategies.

Figure 5. Global technical mitigation potential by 2030 of each agricultural management practice showing the impacts of each practice on GHG



Source: Bellarby et al, 2008

89 % of the mitigation potential from agriculture comes from carbon sequestration; and carbon is held in soil organic matter and in above-ground biomass. Therefore, croplands, grazing lands, soil organic matter restoration and other practices hold a huge mitigation potential (Bellarby et al, 2009) Sinks can comprise the restoration of natural vegetation and improved agricultural management practices. Although the direct potential for carbon mitigation by livestock management is small, at 10%, absolute volumes are significant, and included in this is livestock feed that may either sequester carbon through improved grazing, or increase emissions through the production of grain-based concentrates and their transport.

Table 3. Mitigation activities to increase carbon sinks, reduce energy use and avoid GHG emissions (based on Pretty, 2008; Bellarby et al, 2009)

Activity	Additional comments
Replace inversion ploughing with conservation (CA) and zero-tillage (ZT) systems	ZT/CA can lock up 0.1 to 1 t carbon per ha per year, in addition to cutting carbon dioxide emissions by over 50% t through the reduced use of fossil fuel in ploughing. If another 150 million ha of rainfed cropland is converted to ZT/CA by 2030, a further 30 to 60 Mt carbon could be soaked up annually during the first few years after conversion. Benefits may be counteracted if increased herbicides or machinery used.
Increase total yields per se	To increase carbon sequestered during plant growth as well as residues incorporated. By improving water management, fertilisation, varieties.
Adopt mixed rotations with cover crops and green manures to increase biomass additions to soil	Avoid burning of residues.
Adopt agroforestry in cropping systems to increase above-ground standing biomass	
Minimise summer fallows and periods with no ground cover to maintain soil organic matter stocks	
Use soil conservation measures to avoid soil erosion and loss of soil organic matter	
Apply composts and manures to increase soil organic matter stocks	Soil carbon can be built with the use of soil additives, including silicates, and biochar (Lehman 2007; Garnaut, 2008)
Improve pasture/rangelands through grazing, vegetation and fire management to both reduce degradation and increase soil organic matter	Avoid overgrazing.
Cultivate perennial grasses (60-80% of biomass below ground) rather than annuals (20% below ground)	Includes restoration of arable to grassland
Restoration of natural vegetation	Greenpeace (2008) estimates that the Australian rangelands (covering 70% of Australia's land mass) could absorb at least half of the nation's current annual GHG emissions and 250

	MT for several decades, if land restoration practices were applied. If 2 million of the current 126 million ha of saline soils were restored each year, they could account for an extra 13 Mt carbon annually (FAO, 2002)
Restore and protect agricultural wetlands (including peatlands)	If waterlogging, may stimulate CH_4 emissions (Paustian et al, 2004)
Convert marginal agricultural land to woodlands to increase standing biomass of carbon	Can include set-aside, conversion of field margins, shelterbelts (Bellarby et al, 2009)
Conserve fuel and reduce machinery use to avoid fossil fuel consumption	
Adopt grass-based grazing systems to reduce methane emissions from ruminant livestock	
Use composting to reduce manure methane emissions	Avoid methane emissions of manure by anaerobic digestion (Audsley et al, 2009)
Modify livestock diets	The addition of certain oilseeds. Optimisation of protein intake. Possible use of vaccines, probiotics and others.
Changing livestock breeding and management practices	Increase productivity through breeding. Reduce number of replacement heifers.
Reduce the use of inorganic N fertilisers and adopt targeted and slow-release fertilisers	Nitrification inhibitors on fertiliser may reduce nitrous oxide emissions by up to 80% (de Klein &Eckhard, 2008)
Use IPM to reduce pesticide use	
Cultivate annual and perennial crops and/or use agricultural by-products for combustion and electricity generation	For example, Biochar.
Use biogas digesters to produce methane	

The use of these techniques in combination is analysed in Section 5 in the discussion on organic farming approaches.

Soil carbon

Approximately 82% of terrestrial carbon is held below ground, within the soil (Harvey, 2008). Between 1997-99, an estimated 590 to 1,180 Mt carbon were locked up in cropland soils alone, in the form of soil organic matter from crop residues and manure. Projections of increased crop production imply that by 2030 this total could rise by 50 % (FAO, 2002). Garnaut (2008) goes into more detail on soil carbon, drawing on evidence from Grace et al, 2004, and Jones et al, 2008. Similarly, the Worldwatch Report ‘Mitigating Climate Change Through Food and Land Use’ (2009) also has a strong section on enriching soil carbon. Whilst zero tillage increases soil carbon stores close to the surface, this stock may be returned to the atmosphere within months. By contrast, CO_2 removed by active growing roots of living plants and stored in soil humus can provide long term storage. Essential to this process is increased soil microbial activity to enable availability of soil minerals and other nutrients, and increase water retention and oxygen respiration. Within this, and between the carbon and nitrogen cycles, there are trade-offs that need to be managed at local scales.

Rice production

Wetland rice production is a fairly significant emitter of methane, largely because of the practice of draining during the growing season. Mitigation methods include the development of rice cultivars with low exudation rates, reducing waterlogging, direct seeding, increasing rice productivity, adjusting the timing of residue additions, or composting the residues (Wassman et al, 2004), and these actions may reduce emissions by 0.5 GT CO_2-eq by 2020 (IPCC, 2001).The System of Rice Intensification (SRI) may hold potential to reduce emissions further, as this system does not use flooding (Bellarby et al, 2009). It involves growing rice plants widely spaced and with only organic amendments and is particularly well suited to resource-poor, smallholder farmer conditions (Doberman, 2003). Although no published studies can be found on the implications of SRI for GHG emissions, research to investigate this is currently underway in India (CIIFAD, 2010).

Grazing

Several contentious issues surround livestock production. Ruminants produce methane, and extensive grazing systems require more land and have a higher GHG footprint in terms of kg per product (Garnett, 2010). The FAO report ‘Livestock’s Long Shadow’ (2006) calculates that intensively reared livestock contribute 5% to global GHG emissions, and extensive systems 13%. However, this is arguably outweighed by the value of ruminants in transforming plants and wastes that are inedible to the human digestive system into useful products: manure, meat, milk, materials, particularly on land unsuitable for crop production. Depending on how they are managed, livestock also cleanse land of pests and diseases and weeds, and, if desired, maintain landscapes including upland peat areas that are in themselves important carbon sinks. Livestock are, of course, also a source of traction, and can survive on land unsuitable for cropping. The solution, as Garnett sees it, is to cap meat demand and maintain grazing animals for their resource efficiency. Harvey (2008) suggests that permanent pasture grazing systems can also increase the production of glomalin that is itself a carbon store (as discussed in Box 2). The relation between grazing and soil-carbon is location-specific and difficult to generalise.

Fertiliser production

Energy usage in fertiliser production is a result of the Haber-Bosch process (of synthesising ammonia to nitrogen), and is dependent on hydrogen from natural gas. Glendining et al (2009) estimate that if alternative sources of hydrogen are to be used, this will require 2% of total global energy consumption by 2050. Improvements in fertiliser production hold the potential to reduce its GHG emissions by more than half, through greater energy efficiency in ammonia plants (29%), improved nitrous oxide reduction technology (32%), and other energy saving measures in plants (39%) (Kongshaug, 1998). Organic amendments provide alternatives to industrially manufactured fertiliser inputs.

On-farm energy

Agriculture itself is not generally considered important when looking at reductions in energy emissions. For example, Heaps et al (2009), when assessing the reduction potential for Europe, point out that the energy demand for agriculture is less than 2.2% of total final energy demand in the EU, and that very few case studies of GHG emissions address agricultural energy use in any detail. They do not include it in their study but assume significant oil and diesel using equipment will switch to electric-powered versions by 2050. The authors refer to Brown & Elliot (2005) who calculate that increasing efficiency in irrigation pumps, motors, and other agricultural machinery can yield 16 per cent reductions in energy use in 2020 and 35 per cent in 2050.

Finding a balance

Discussion continues in the literature as to whether to go for intensification of existing agricultural land, or whether to continue to bring new land into cultivation. Intensifying existing agricultural land may mean continuing to use farm inputs and machinery that have a high carbon cost and that are unsustainable over the long term. On the other hand, bringing new land into production may also have a carbon cost, and a higher one. Vleke et al (2004) calculated that for less industrialised countries, intensification, through the use of an additional 20% of fertiliser, increased production to the extent that the carbon sequestered in the set-aside land far outweighed the emissions relating to fertiliser use. In SSA for example, a 20% increase in fertiliser use can tie up between 8–19 Mt CO_2pa.In a study that looked at the relationship between crop yields, land use change and GHG emissions, Carlton et al (2009) argue that if yields decline on currently farmed land – through attempts to reduce nitrogen fertiliser usage or to extensify, then uncropped land would need to be brought into use and this would result in significant GHG emissions. This study was based on the conversion of pasture to wheat production. Therefore, the authors concluded that crop yields need to be maintained or increased in any climate change mitigation strategy, rather than extensify and clear land. Both Smith et al (2007) and the Royal Society report (2009) also propose sustainable intensification as the route forward.

Smith et al (2007) identify other trade-offs and co-benefits, such as the build-up of soil carbon that also increases crop productivity, and increasing sequestration that also helps to conserve soil and reduce erosion. Deep rooted, grazing perennials also replenish organic matter and improve soil quality. On the other hand, intensifying productivity through increasing inputs may lead to soil depletion through acidification or salinisation. Intensification may be positive or negative in terms of carbon emissions and capture, depending on how it is done. There is also a temporal factor; soil carbon sequestration, for example, offers an immediate mitigation potential but is time limited and has a saturation level; whereas reducing emissions from energy infrastructure may take longer to implement but may have a longer term impact.

Overall, GHG mitigation practices on farm lands exert complex, interactive effects on the environment, sometimes far from the site at which they are imposed. The merits of a given practice, therefore, cannot be judged solely on effectiveness of GHG mitigation. Marginal Abatement Cost Curves may be useful in calculating the cost-benefits of different options, with some mitigation options being cost-negative and others cost-positive (Midgeley & Moran, 2008). If abatement schemes are implemented, projections indicate that for some farming systems and crops in industrialised countries, yields and profit margins will decline (Metcalf & Kingwell, 2009; Neufeldt & Schäfer, 2008).

Regional variations

In the U.S., if farmers widely adopted the best management techniques to store carbon, and undertake cost-effective reductions in nitrous oxide and methane, aggregate U.S. greenhouse gas emissions could be reduced by 5 to 14 % (Paustian et al, 2006).

In an assessment of mitigation strategies for Europe, Smith et al (2000) concluded that the most important resource for carbon mitigation in agriculture is the surplus arable land that could be put into alternative long term land use instead of short term rotational set-aside. Alongside this, no single land management change in isolation could mitigate all the carbon required to meet Europe's climate change commitments.

In Africa, Batjes (2004) estimated the soil carbon gains from improved management and restoration of degraded crop and grassland. This had a mitigation potential of 4–9% of Africa's annual CO_2 emissions. Specific management practices included conservation tillage, cover cropping, green manuring, planting of hedgerows, organic residue and fallow management, mulch farming, water management, soil fertility management, agroforestry, adapting crop rotations, soil conservation, controlled grazing, improving pastures, and fire management.

The food system and dietary trends

Concerns over dietary trends tend to focus on livestock and meat production. A vegetarian diet produces fewer GHG emissions over a lifetime: an average of 25kcal fossil energy are used per kcal of meat produced, compared with 2.2kcal for plant based products (Pimentel & Pimentel, 2003). Jackson et al (2005) calculate that if less industrialised countries were to consume as much meat as industrialised, we would need two-thirds more agricultural land than we have today. Even 385 kcal of fossil fuel per person per day could be saved by substituting 5% of meat in the (U.S.) diet with vegetarian products (Bellarby et al, 2009). Stehfest et al (2009) used an integrated assessment model to analyse the relationship between meat consumption and climate change. They found that a global food transition to less meat – a fall from the current 245g per person per day to 102g per day - would have a dramatic effect on land use, freeing up pasture and cropland for carbon sequestration uses and substantially reducing nitrous oxide and methane emissions. This global transition to a low-meat diet would reduce GHG mitigation costs by 50% compared to other dietary approaches, to achieve a 450 ppm CO_2eq stabilisation target by 2050.

The Report 'How Low Can We Go?' (Audsley et al, 2009) examined the supply chain measures required to achieve a 70% reduction in emissions. These measures ranged from the decarbonisation of transport to technologies to reduce methane emissions. Results showed that a radical structural change throughout the food supply chain would be required, with no single measure capable of reducing emissions by more than half. However, the authors calculate that this consumption-based approach has the potential for savings that are greater than a focus on production. They also calculate that a vegetarian diet would reduce supply chain emissions by 15–20%.

On a local level, and to better understand the climate impact of food in Washington (Born et al, 2008), researchers at the University of Washington assessed and compared greenhouse gas emissions of locally and globally sourced food items. Using the Life Cycle Assessment method, they compared four typical Washington food items sourced regionally and globally. The more locally produced products had less climate impact in every case, though the reasons vary and in this case depended largely on Washington's high agricultural productivity. In Cardiff, Collins & Fairchild (2007) assigned an ecological footprint to a range of typical foods and explored modified versions of that diet. The study found that a nutritionally adequate diet could be achieved with a carbon footprint reduction of 23% lower than the Cardiff average, and that this would also be cheaper. An organic diet would be more expensive, and vegetarian would only reduce the footprint by 8% because dairy consumption would increase under this scenario.

5. Projections for Feeding Under Different Scenarios: Issues to Consider

Recognition of the link between food security and broadscale agricultural GHG mitigation

Overall, no studies were found that address the core issues of feeding nine billion through a low-emissions production approach. The reasons why these have not yet been considered together are fourfold: partly due to the sectoral nature of development: food security actors tend to focus on climate change adaptation rather than mitigation, whilst climate change researchers have not projected mitigation strategies; partly because the drivers of research on emissions reduction are largely economic and technology focussed, resulting in relatively more studies on, for example, the potential and impact of biofuels; partly because the agricultural sector is not seen as a major emitter of GHG compared to other sectors; and partly because agricultural mitigation strategies are considered to be fraught with complexity and there is as yet a weak knowledge base on their interactions. In work on emissions reduction and carbon abatement, agriculture does not feature as a significant activity and there are assumptions that other sectors and activities would be more cost-effective to address. As one modeller responded to a request for such information:

> "We do not focus on agricultural production and the food system in our analysis. While it is true that agricultural activities can be energy- (and particularly fuel-) intensive, this sector constitutes a small fraction of aggregate emissions and it is likely that lower cost abatement options may be found elsewhere. Of course, the issue of emissions associated with land use is a different matter, and one on which there has been considerable debate surrounding the net contribution of biofuels to carbon mitigation." (Personal communication, 02/10)

Literature on agricultural production and as well as that on climate change discusses the positive and negative impacts of climate change and ways that agriculture could adapt and even sequester carbon. Several authors do recognise the dual potential and challenge of agriculture to mitigate climate change and feed the population by 2050, including Medvedev et al, 2009. As the Stern Review states: "One of the world's largest challenges, besides reducing fossil emissions, is to achieve a global transformation of world food production. Agricultural land use systems – today accounting for 17–30 per cent of global GHG emissions – need to rapidly shift from being a net source of emissions to potentially becoming a net global sink. This needs to occur in a situation where (1) a new green revolution is needed to lift 1 billion out of hunger and feed a world population of ~9 billion in 2050; (2) options for sustainable expansion of agricultural land are extremely limited due to current disastrous rates of biodiversity loss and ecosystem degradation; (3) unavoidable climate change will undermine the stability of freshwater availability for agriculture – the world's largest water-dependent human activity." (HM Treasury, 2006). Kartha et al (2009), add

> "While this clearly confronts human society with an almost overwhelming challenge, there is no evidence suggesting it is impossible. To the contrary, the growing body of analytical work examining such scenarios at the global and regional level suggest it is not only technically feasible but also economically affordable, even profitable. The affordability of an ambitious response is even clearer when the costs of inaction are considered. These conclusions, however, only apply assuming a global transformation towards sustainability begins in the very near future and accelerates quickly."

Yet all the papers reviewed do not go further to forecast whether – and how – a low emissions agriculture can supply the future food demand.

Scale and speed

In their discussion of the cost benefits of GHG mitigation, Ackerman et al (2009) argue that steps must be taken to speed up GHG mitigation measures. The most rapid methods to remove CO_2 from the atmosphere are reported as being reforestation and biochar production (Bellarby et al, 2009), and both of these measures are not exclusive to agriculture but can be integrated into, for example, agroforestry practices.

Several authors have noted that mitigation actions are locally dependent and their impacts cannot be extrapolated. Yet few studies compare scale and intensification of production approach in relation to GHG mitigation. Smallholder farms may store more carbon than commercial arable owing to the greater presence of trees (Roshetko et al, 2002), although this will be affected by their degree of productivity. Generally, traditional farming systems use less energy per unit of product (not necessarily per ha) owing to the reduced use of machinery (Mrini et al, 2002). In Cuba, Ríos et al (2001) calculated that smallholder agro-ecological farmers used only 25% of the energy of industrial farming systems for the production of certain staples, yet achieved the same yields. In this study, energy usage comprised fertiliser, pesticide and irrigation applications.

Advances in modelling?

Numerous global-scale scenarios of GHG emissions exist, including the IS92 series and SRES of the IPCC (IPCC, 2000; 2001). These scenarios tend to focus on reductions across all sectors and largely in terms of conversion from fossil to renewable energy supplies. These scenario-based quantified findings rely on a modelling framework which includes as components, the FAO/IIASA Agro-ecological Zone model (AEZ) and the IIASA world food system model (WFS). The modelling framework encompasses climate scenarios, agro-ecological zoning information, demographic and socio-economic drivers, as well as production, consumption and world food trade dynamics (Fischer et al., 2009; Fischer et al., 2005). (The International Institute for Applied Systems Analysis' (IIASA)'s modelling framework and models have been developed to analyse spatially the world food and agriculture system and evaluate the impacts and implications of agricultural policies.)In the US-EPA study, Annex 278 provides the methodology for calculating sources or sinks, including estimating net changes in carbon stocks in mineral and organic soils on cropland and grassland. Finally, the Millennium Ecosystem Assessment (Bennett & Carpenter, 2005) provides data for assessing land use change and climate change goals; it draws up four global scenarios through which to assess the possible evolution of ecosystem services during the twenty-first century.

However, the studies reviewed either do not include food targets or do not consider agricultural mitigation scenarios. This includes the models presented in the Special Issue on Climate Change and Modelling of the Energy Journal, that presented the results of collaboration under Stanford University's Energy Modelling Forum (Weyant et al, 2006). Models reviewed also included Gusti et al 2008, Lee et al, 2007, Lee et al 2005, Cretegny 2009 and Monfreda et al 2007, who note that datasets are being used for global carbon cycle modelling and, separately, for analysis of regional food security. For example, in addressing global food demand, productivity and scarcity of land and water resources, Lotze-Campen et al (2008) developed a model to simulate the combined effects of pressures on production in a spatially explicit way. The model covers the most important crop and livestock production types in 10 economic regions worldwide, and considers crop yields, land and water constraints, economic conditions, and changing productivity associated with climate change. The authors applied the model to different possible future scenarios to 2055 and derived rates of required technological change in order to meet future food demand. However, they did not account for different emissions reduction technologies. Similarly, Kartha et al (2009) at the Climate Impact Research, Stockholm Environment Institute, and Potsdam Institute, Germany developed a Regional Modelling Comparison Project that employed five distinct energy-environment-economy modelling approaches to assess the feasibility of reaching ambitious emission pathways, designed to stabilise atmospheric concentrations of greenhouse gases at 400 ppm-equivalent, and Parry et al (2004) analysed the effects of climate change on global food production under SRES emissions; however, neither considered scenarios for reducing emissions. In developing a new approach to capture the opportunity cost of land use decisions, Golub et al (2008) aimed to analyse competition for land types and input substitution between land and other factors of production. They have developed a computable general equilibrium model with regional land types and detailed GHG emissions. Using this framework, they can estimate general equilibrium abatement supply for CO_2 mitigation in agriculture. This and other such models have been developed in the interests of carbon markets rather than for food security. Finally, the IAASTD report provides scenarios for food production under high investment in agricultural science and technology, but does not disaggregate for low emissions approaches.

An internationally-authored paper lead by the Joint Global Change Research Council, Maryland (Moss et al, 2010) discusses the next generation of scenarios for climate change research and assessment. Noting that scenarios to date have not adequately examined climate change mitigation, they describe a new process for creating plausible scenarios to investigate this. The process combines the development of climate scenarios based on 'representative concentration pathways' (RCPs) with new socio-economic scenarios, in order to explore socio-economic uncertainties acing both adaptation and mitigation.

Overriding these developments, there are a great many multi-level variables and uncertainties within these global models, such as labour productivity and supply, GDP growth, international energy prices, household consumption patterns and technology efficiency improvements (Masui et al, undated). This limits the usefulness of the models in directing national and regional policy and practice, where regional-scale models and other decision-making tools are required. All along the way, authors stress that quantitative data is highly uncertain because of the degree of extrapolation and generalisation required. For example, in Lal's calculation of emissions from farm operations, he extrapolated irrigation over total cropland and arable land (2004), whereas this is not the case in practice. Stanton & Ackerman (2009) note that data and scenarios are dubious and that neither science nor economic models can answer ethical questions. Key areas of uncertainty in climate-economics models were identified as questions of abatement technologies and costs, including a focus on the "cost effectiveness" method of economic analysis; and ethical issues surrounding the distribution of the costs of emission reductions and adaptation measures. Similarly, the Stern Review notes that modelling the impact of climate change is a formidable challenge involving forecasting over a century or more, and that the limitations to our ability to do this demand caution in interpreting results. A World Bank Discussion Paper on climate change response (Tubiello et al, 2008) points out that recent global assessments of climate change and food security rely on a single modelling framework, the IIASA system, which combines the FAO/IIASA AEZ model with various GCM models and the IIASA BLS system, or on close variants of the IIASA system. This has, according to the report, important implications for uncertainty, and there is a need for continued and enhanced validation efforts of the tools developed at IIASA and widely employed in the literature. Nevertheless, IIASA (2009) has developed a scientific tool known as GAINS Mitigation Efforts Calculator, which analyses mitigation efforts up to 2020 for a range of criteria for Annex I countries.

At a local level, the UK's Climate Friendly Food group has developed an online carbon calculator for use by food producers at all scales to improve decision-making on low emissions and carbon capture production activities (http://www.climatefriendlyfood.org.uk). Similarly in the UK, the Country Landowners' Association has supported the development of a web-based on-farm GHG audit called CALM (Carbon Accounting for Land Managers) (http://www.calm.cla.org.uk/), and the University of Aberdeen's Sustainable Food Lab is testing an industry-supported accounting tool "Cool Farm Tool".

Proxy whole-farm systems analyses

A proxy means of assessment of whether low emissions agriculture can feed nine billion can be made by drawing on the handful of attempts to assess whether sustainable agricultural systems can feed the world. There are two challenges to using proactively sustainable systems as a proxy. First, farmers may use a range of techniques - some more sustainable than others –and this presents a challenge to identifying a baseline of sustainable whole farm systems. Second, some techniques classified as 'sustainable' may actually contribute to GHG emissions, such as the bulk handling of slurry and manure.

Pretty et al (2006) worked around this challenge by attempting to relate sustainable production methods with GHG emissions across 286 interventions in 47 lower-income countries, covering 37 million ha (or 3% of cultivated area of less industrialised countries). Only specific production methods on the farm were measured, not the whole farm. The sustainable production methods sequestered an average of 0.35 t CO_2 ha/pa whilst increasing crop yields by 79%. The authors were cautiously optimistic that future food needs could be met under these production regimes. Conservation and no-till or zero-till agriculture as a movement is growing, supported by the FAO. Because of its less dogmatic stance on agro-inputs and the general absence of philosophical standpoint, it is seen as the conventionally-acceptable face of organic farming. However there is little documentation on the potential of conservation agriculture to feed the world. An FAO workshop on conservation agriculture and minimum tillage (FAO, 2008a) did pose the question of whether plough-based farming systems could be replaced with more sustainable systems in order to safeguard the world's future food supplies, but then did not proceed to answer it.

The best defined bodies of intentionally sustainable, whole farm systems are the certified and non-certified organic, agroecological and biodynamic farming movements. Farmers within these movements follow specific, transparent principles and/or guidelines on sustainability across the whole farm system, or share a belief system that drives their decision-making toward a style of agriculture that works with nature (biomimicry) and avoids harm to nature. Especially for industrialised regions, organic farming has only recently woken up to the issue of energy challenges for the future, and therefore organic farms do not necessarily employ sustainable energy management systems (Ziesemer, 2008; Hall & Mogyorody, 2001). Yet results of two studies on this issue indicate that organic agriculture performs better on a per hectare scale with respect to both direct energy consumption – fuel and oil – and indirect consumption of fertilisers and pesticides (Ziesemer, 2008; Scialabba & Hattam, 2002). A comparative analysis of energy inputs on long-term trials at the Rodale Institute found that organic farming systems used 63% of the energy required on conventional farms, largely because of the savings made in the energy input of synthetic nitrogen fertiliser (Pimentel et al, 2005).Organic farms have been criticised as playing into the industrialised, high-fossil energy dependent, food system, and organic commodities may be similarly associated with a high overall GHG footprint. Nevertheless, the majority of mitigation activities listed in Table 2 of this review are cornerstones of organic agricultural practice, and therefore these production systems arguably serve as the best widespread examples of low emissions agriculture to date. Organic systems also tend to be more resilient than industrial in terms of withstanding environmental shocks and stresses including drought and flooding; since the systems are not optimised for production, but also include resilience in, for example, their soil water reserves, and because of the conservation measures that hold the system together such as terracing and the use of deep rooting plants and overall diversity (Ching, 2004; Lotter et al, 2003; Holt-Giménez, 2002).

From Deutsche Bank's report 'Investing in Agriculture' (2009), Kahn &Zaks discuss an alternative model of a food system such as those promoted by organic agriculture, that is local, energy-efficient, multi-cropping, low-carbon, socially just and self-sustaining. Erb et al (2009) have perhaps undertaken the most comprehensive comparison of sustainable agriculture scenarios, in 'Eating the Planet: Feeding and Fuelling the World Sustainably, Fairly and Humanely – a Scoping Study.' Based on several large and consistent databases for the year 2000, they have developed a model that calculates the balance between global biomass demand (food and fibre) and global biomass supply from cropland and grazing land, for 11 world regions, 11 food categories, 7 food crop types and 2 livestock categories, as well as global bioenergy potential from cropland and grazing areas. Forestry was not included. The study evaluated the possible effect of climate change on yields. Based on this, a set of assumptions was developed to analyse the situation in the year 2050. This included the UN population forecast of 9.16 billion, and the FAO forecast of average crop yield growth of 54%, and cropland area growth of 9%. This was compared with two other crop production scenarios, 'wholly organic' and an intermediate scenario. Four different diets were assessed: ranging from 'western high meat' to a nutritionally sufficient 'fair less meat' low in animal protein. Three different livestock regimes were assumed: intensive, humane and organic. Two estimates were included of cropland expansion, to +9% and +19%. This all resulted in 72 different scenarios, each of which was considered feasible if the calculated cropland demand came to 95% or less of that available in 2050.

Results suggested that feeding the world with organic crops and livestock was probably feasible, though this would require a high growth in global cropland area by 20%, and would presume that food would be distributed equally, that modest diets were adopted, and that the diet would consist of 20% animal protein. The 'western high meat' diet would require a similar cropland area and would require a combination of massive land use change, intensive livestock production systems and intensive use of arable land. The authors noted that climate change could have a positive or negative impact on global food systems depending on the presence or absence of CO_2 fertilisation. They also concluded that it was not necessary to maximise intensity of production.

In the UK, Simon Fairlie has attempted to assess whether Britain can feed itself on a range of sustainable production systems. In his paper in The Land (2007), he based his template for calculations on a book of the same title by Scottish ecologist Kenneth Mellanby, written in 1975. Fairlie placed a basic diet under six different agricultural regimes – chemical, organic, and permaculture, each with or without livestock. The main conclusion was that organic, livestock-based agriculture had the most difficulty in sustaining the UK population on the land available, while all the other management systems (including vegan organic) could do so with a comfortable margin. Vegan organic was considered fairly difficult to achieve however, although there has been little research in this area.

The following year, The University of Reading was commissioned by the Soil Association to undertake a comparative study without the permaculture option (Jones & Crane, 2009). The report quantified the food that could be supplied by a wholly organic agriculture compared with the current. Data came from 176 working organic farms. Results showed that a wholly organic agriculture would produce around 60% of currently levels of conventional cereal production, resulting in a fall in national self-sufficiency of 65%. Organic vegetable supplies would equal conventional. In the dairy sector, organic could produce 65% of conventional milk volumes, and for livestock 68% more beef and 55% more sheepmeat than current. Pig and poultry sectors would decline to 30% of current production. This system would be less energy demanding, and farm employment would be 70% higher. It would also have a lower carbon footprint than conventional agriculture, although a fall in UK production would imply an increase in food imports and their associated carbon costs. For both these studies, food self-sufficiency may take higher priority on the global agenda if transport emissions become a challenge, or if countries increasingly take on a food sovereignty approach.

Within the organic movement, a few studies have attempted to assess whether organic farming can feed the world. The most widely quoted study is that by Badgley et al. (2007) of the University of Michigan that assessed whether organic agriculture could contribute significantly to the global food supply. It compared yields of organic versus conventional food production for a global dataset of 293 examples. Results indicated that organic methods could produce sufficient food on a global per capita basis to sustain the current population, and potentially an even larger population, without increasing the current agricultural land base. The study also evaluated the nitrogen availability, results indicating that leguminous cover crops could fix sufficient nitrogen to replace the amount of synthetic nitrogen currently in use. Other studies have focused yield comparisons, and indicate that organic or ecological approaches can achieve significant yield increases over both traditional and industrialised agriculture, particularly in resource-poor regions of the world (Parrot & Marsden, 2002; Pretty et al, 2002a; Rundgren, 2002; Mäder et al, 2002; McNeely & Scherr, 2001; Altieri et al, 1999; Pretty & Shaxson, 1997). These all indicate that an organic style of agriculture, as a proxy of a low-emissions agriculture, can feed the world if a change in diets and land use is accepted.
Two major studies have attempted to address the issue of organic farming and climate change. The first, by the FAO, seeks to answer the question of whether low GHG emission agriculture is possible and desirable, by examining current farming practices and scientific databases from long term field

experiments as case studies for low GHG agriculture. It also examines the changes required for low GHG agriculture systems to become a reality, and elucidates on the adaptive capacity of agro-ecological farming system approaches (Niggli et al, 2009). The report calculates that the minimum scenario for a conversion to organic farming would mitigate 40% of global agriculture GHG emissions, and that another 20% of agricultural GHG would be reduced by abandoning synthetic nitrogen fertilisers. Juxtaposed with this, a 100% conversion would decrease yields between 30–40% in intensively farmed regions under the best agroclimatic conditions. However, in less favourable regions, yield losses would be zero. The report quotes numerous case studies that show that, in comparison to traditional subsistence farming, organic yields were 112% higher.

The second study, commissioned by the Soil Association, is a review of the evidence of the relationship between agriculture and soil carbon sequestration, and how organic farming can contribute to climate change mitigation and adaptation (Azeez, 2009). Although with an explicit policy agenda to promote organic farming, this comprehensive document (of 212 pages) reviews 1287 papers and provides a detailed explanation of the relationship between soil carbon and climate change, and the agricultural practices that reduce soil carbon. The document assesses comparative studies on soil carbon in organic farming, and reviews the approaches that build the soil carbon store. It also discusses carbon sequestration. The main conclusions include that soil carbon impacts of agriculture are ignored by current GHG accounting systems, so that GHG emissions of agriculture have been greatly under-estimated and the emissions of organic farming greatly over-estimated. The review of all available comparative studies indicates that, on average, organic farming produces 28% higher soil carbon levels than non-organic farming in Northern Europe, and 20% for all countries studied. On this basis, the author conservatively estimates that the widespread adoption of organic farming in the UK would offset at least 23% of UK agriculture's GHG emissions. If adopted globally, the offset potential would be 11% of all global GHG emissions for at least the next 20 years. However, and as with the study by the University of Reading, any yield reduction would have to be compensated by increased food imports and their associated carbon costs.

Capturing cutting edge research and development

Within these non-mainstream farming movements, and more widely, experiments are being undertaken that are simply not documented, let alone appear in peer-reviewed journals. Outside of the professional development sector, academia, and political networks, there are millions of professionals implementing practical R&D work, learning by doing and by accrued experience, using common sense, drawing from grey literature, and occasionally receiving scientific 'evidence' that filters through to them by means of conferences, industry articles, radio and other channels. The principles, theories and practices they are developing and using are ground tested and, if captured, would greatly benefit the current body of knowledge that is used as a basis for forecasting and policy development.

Two relevant examples of practical R&D are provided here, that of high carbon capture grazing systems, and of land restoration. Neither of these cases are supported by any peer-reviewed evidence, nor is there substantial research monitoring and measuring these systems. These examples serve to show that practice is ahead of the evidence available to policy decision-makers, and indicates that decisions need to be made on how to improve this situation.

Box 2 The case of mob grazing

In the discourse on livestock production and GHG emissions, what has been less discussed is the capacity of livestock to maintain grazing lands as carbon sinks. The concept of 'mob grazing' is being designed to mimic the productivity of the American prairies in pre-colonial times, when organic matter averaged 10% and land supported a weight of buffalo heavier than the combined weight of the entire human population of the USA and Canada today (Harvey, 2008). Huge herds of buffalo would intensively graze — and fertilise — the permanent pasture, and then move on, enabling the diverse range of grasses to recover and grow back. As grass is grazed above ground, so it reflects this in a shedding of carbon-rich roots and hyphae below ground. The hundreds of grass species with their varying root lengths and breadths thus continually put carbon back into the soil as they were sporadically grazed and then rested. This phenomena was recognised and documented by Allan Savory (1999). Mob grazing is being practised by the Carbon Farmers of America and of Australia. http://www.carbonfarmersofamerica.com/
http://www.carbonfarmersofaustralia.com.au
Opposing the accepted view that grazing results in higher methane emissions, a New Zealand agronomist promoting mob grazing has collected empirical evidence that shows the opposite: that grazing systems have up to 40% lower carbon footprint than intensive systems when all the external inputs and activities are evaluated (Philips T. Milk Production Carbon Footprint Summary. Pasture to Profit www.pasturetoprofit.co.uk). Supporting this evidence, Harvey (2008) points out that the fumeric acid currently being marketed as being able to reduce livestock methane emissions, is found widely in nature in the mixed grazing swards and hedgerow plants, and that part of the methane problem is because livestock have been fed ryegrass monocultures instead of these mixed swards.

Key to mob grazing and soil carbon capture is the presence of glomalin, a recently-discovered glycoprotein compound produced by mycorrhizal fungi as they supply water and nutrients from the soil to the plants in return for plant sugars. Glomalin contains 30–40% carbon (compared to 8% in humic acid), or 27% of the all soil carbon, and can survive in the soil for more than 40 years. Without a healthy population of arbuscular mycorrhiza in soils, glomalin cannot accumulate, and plants cannot thrive. Research at the University of California found that when atmospheric CO_2 levels rose, fungi increased their production of glomalin. At 670 ppm of CO_2, fungal hyphae grew three times as long and produced five times as much glomalin, indicating that the higher the concentration of carbon in the atmosphere, the greater the storage rate in the soil. Glomalin production is also induced by no-till methods of farming (Wright, 2002). Glomalin was discovered in 2002, yet it still does not feature in discussion on carbon capture; perhaps because it cannot yet be synthesised as a commercial product.

With regard to land use, the restoration of natural vegetation on neglected land is seen as good practice to mitigate GHG emissions. Yet a more productive approach would be to restore land to agricultural value, by installing appropriate production systems that both capture carbon and that are low-emitters during their installation period. One innovative method practised by the Permaculture Research Institute of Australia is a rainwater harvesting and conservation system, as seen in a project example from Jordan. Although this project commenced in the early part of the previous decade, it has only been documented once, in 2008 by the ProAct Network that promotes environmental security and climate solutions for civil society (ProAct Network, 2008).

Box 3: Cutting edge water harvesting and soil conservation in Jordan

The goal of the Jordan Valley Project was to demonstrate the potential for improving human and environmental conditions using low-cost, low-tech approaches on a 4 ha desert site under high salinity and drought conditions. Rainfall was 100–150mm/pa occurring in two or three periods. Soils were of low fertility and vegetation was mainly absent apart from salt-tolerant species.

To counter this, eight rainwater harvesting contour swales (ditches on contour) were constructed, 2–3 m wide and 0.5m deep, running across the farm from north to south, approximately 100m–250m in length. These were connected to an erosion gulley, and thus collected all the runoff and storm water from over a larger area of land. The swales were lined with mulch, and captured water infiltrated and stayed in the soil profile, thus reducing evaporation. An irrigation water storage dam was constructed and stocked with tilapia, and a drip irrigation system installed. The upper side of each swale was planted with legume forest pioneer tree species in order to fix nitrogen and reduce evaporation. On the lower sides, fruit trees were planted. Vegetables were planted on the swales, and barley and alfalfa between swales. Livestock raised on the farm comprised chickens, pigeons, turkeys, geese, ducks and rabbits. Sheep and a dairy cow were introduced after sufficient forage became available.

After two years, the plant growth success rate was calculated as 90%. Only 1/5 as much irrigation water was required as on surrounding productive areas in the region. Soil salinity levels decreased, as did soil pH levels. Crop yields were similar to those under conventional agriculture on neighbouring farms. The carbon benefits were not directly measured but huge amounts of biomass were generated both above and below ground, as was soil organic matter. This work is featured on You Tube and been viewed 150,000 times: http://www.youtube.com/watch?v=sohI6vnWZmkThis drought-stricken, desert land was greened within a year to create a productive food system and, in doing so, also became a carbon sink.

The relevance for this review is to identify how these experiences can be captured, evaluated and utilised to best advantage in order for more informed policy-making and forecasting on climate change mitigation and future food production, because agricultural knowledge and practices that are currently used in models are behind the times.

Emerging works to look out for

At the time of this review, a handful of other groups and individuals were in the process of developing similar work as follows:

1) The Challenge Programme on Climate Change, Agriculture and Food Security of the CGIAR (CCAFS, 2009) has as one of its projected outputs (output 3, project 6) the development of tools, models and principles to enhance understanding of the trade-offs and synergies between mitigation and adaptation; and among the goals of environmental sustainability, reduced emissions and livelihood improvement.
2) R. Lal, Ohio State University, in preparation
3) Thomas Hertel, Center for Global Trade Analysis (GTAP), Purdue University. May have a product by June (the Agricultural & Applied Economics Association (AAEA) Presidential Address) (personal communication 19/2/10)
4) The UK Office of Science and Technology has commissioned a series of reviews on this issue – the UK Foresight Project outputs - that will be published in Phil. Trans. Royal Soc.B in August/September 2010 (personal communication, Prof Pete Smith, 21/2/10; Jules Pretty 17/2/10)

Conclusions

Just how nine billion will be fed in 2050 with much lower net emissions from agriculture and the food system is not known in any detail. Somewhat surprisingly, although there are studies of the needs of future food production and of the mitigation potential in agriculture, the two strands of work have not been brought together sufficiently to give more than broad indications of what a low carbon agriculture would look like.

Technical options exist to mitigate net emissions from agriculture: much work has been done in the last quarter century and longer to develop a menu of options; and there are many pilot programmes trialling innovations that have yet to be fully recorded or disseminated. There are thus reasons for optimism that both goals of feeding people and reducing net emissions can be met. Since however the details are not clear, there is little work on the policy implications. These deliberations begin with the imponderable of future diets — it is a lot easier to meet the twin goals if diets across the world were to converge on one that includes much less animal products than that consumed in most OECD countries. A similar conundrum arises with the future distribution of food: do we have to accept that in future the food system will continue to produce more than enough food for all, but that one billion persons will go hungry, while many millions grow more obese than is healthy?

Clearly there is a pressing need to define the details of a future agriculture, to assess policy implications, and begin the debates on how changes can be made.

Overall, the issue is hugely complex that needs to be dealt with largely at local, national and regional levels. Every community, let alone region, is unique in agroclimatic zone, land use, socio-cultural influences, food system structures, climate change impacts, levels of emissions, and potential for mitigation. Literature exists on how to deal with complexity, and on how to share and exchange knowledge and experiences between zones. If attention is paid at lower scales, the global ‘problem’ may well take care of itself.

References

Ackerman F., E.A. Stanton, S.J. DeCanio, E. Goodstein, R.B. Howarth, R.B. Norgaard, C.S. Norman & K.A. Sheeran. (2009) *The Economics of 350: The Benefits and Costs of Climate Stabilisation*. Economics for Equity and Environment, Stockholm.

Aggarwal P.K., P.K. Joshi, J.S.I. Ingram & R.K. Gupta (2004) 'Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formation'. *Environmental Science and Policy*, 7, 487-498

Altieri, M.A. Companioni, N. Canizares, K. Murphy, C. Rosset, P. Bourque, M. and Nicholls, C.I.(1999) 'The greening of the "barrios": urban agriculture for food security in Cuba', *Agriculture and Human Values*, 16, pp131-140

Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, C., and Williams, A. (2009).*How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050.FCRN/*WWF-UK.

Azeez G. (2009). *Soil Carbon and Organic Farming*. The Soil Association, Bristol.

Badgley, C. Mohhtader, J. Quintero, E. Zakem, E. Chappell, M.J. Aviles-Vazquez, K. Samulon, A. and Perfecto, I. (2007) 'Organic agriculture and the global food supply', *Renewable Agriculture and Food Systems*, vol 22, no 2, pp86-108

Barrett C.B. (2010) 'Measuring food insecurity.' *Science*, Vol 327, 825-828

Batjes N.H (2004) 'Estimation of soil carbon gains upon improved management within croplands and grasslands of Africa.' *Environment, Development and Sustainability*, 6: 133-143.

Bellarby J., B. Foereid, A. Hastings & P. Smith (2008). '*Cool Farming: climate impacts of farming and mitigation potential*'. Greenpeace International, Amsterdam.

Bennett E. & S. Carpenter (2005) *Scenarios for Ecosystems Services, Rationale and Overview. Chapter 5.Scenarios Assessment of the Full Report*. Millennium Ecosystem Assessment. Island Press, Washington DC. http://www.millenniumassessment.org/en/Scenarios.aspx

Born B., P. Monsivais & D. Morgan (2008) *Greenhouse Gas Emissions and the Local Food System*. King County Acting Food Policy Council, University of Washington, Seattle.

Brown E. & R.N. Elliott (2005) *Potential Energy Efficiency Savings in the Agricultural Sector*. Report IEO53. American Council for an Energy Efficient Economy. Washington DC.

Bruinsma J. (2009) 'The Resource Outlook to 2050, How Much Do Land, Water and Crop Yields Need to Increase by 2050?' Paper presented at the FAO Expert Meeting, 24-26 June 2009, Rome on "How to Feed the World in 2050". FAO, Rome.

Boko, M., I. Niang, A. Nyong, C. Vogel, A. Githeko, M. Medany, B. Osman-Elasha, R. Tabo and P. Yanda (2007) *Africa. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge UK, 433-467

Cabinet Office (2008) *Food Matters. Towards a Strategy for the 21st Century*. Cabinet Office Strategy Unit, London.

CCAFS (2009) *Provisional Medium Term Plan: 2010–2012*. Challenge Program on Climate Change, Agriculture and Food Security (CCAFS) The Alliance of the CGIAR Centers and ESSP, Rome and Paris.

Carlton R., P. Berry & P. Smith (2009) 'Investigating the interplay between UK crop yields, soil organic carbon stocks and greenhouse gas emissions.' *Aspects of Applied Biology* 95, 59-64

Ching L.L. (2004) *Organic Outperforms Conventional in Climatic Extremes*. Institute for Science in Society, www.i-sis.org.uk/OrganicOutperforms.php Accessed March 2008

CIIFAD (2010**)** *Centre for World Solidarity Promotes SRI at Fair and Undertakes GHG research in Orissa*. The System of Rice Intensification. India, 2010 Activities, Progress and Updates. http://ciifad.cornell.edu/SRI/countries/india/index.html Accessed 26/02/10

Cline W.R. (2007) *Global Warming and Agriculture: Impact Estimates by Country. Centre for Global Development*, Washington DC.

Cole C.V., J. Duxbury, J. Freney, O. Heinemeyer, K. Minami, A. Mosier, K. Paustian, N. Rosenberg, N. Sampson, D. Sauerbeck & Q. Zhao (1997) 'Global estimates of potential mitigation of greenhouse gas emissions by agriculture.' *Nutr.Cycl.Agroecosyst*. 49, 221-228.

Collins A. & R. Fairchild (2007) 'Sustainable food consumption at a sub-national level: an ecological footprint, nutritional and economic analysis.' *Journal of Environmental Policy and Planning* 9, 1, 5-30.

Cretegny L., (2009) 'The economics of adaptation to climate change. An integrated assessment framework' In: *The Economics of Adaptation to Climate Change*. World Bank.

de Klein, C.A.M. & Eckard, R.J. (2008), 'Targeted technologies for nitrous oxide abatement from animal agriculture', *Australian Journal of Experimental Agriculture*, 48: 14–20.

DEFRA (2010) *Food 2030: How we get there*. HM Government, London.

DEFRA (2009) *Low Carbon Farming: the benefits and opportunities*. DEFRA, London.

FAO (2009) *How to Feed the World in 2050*. High Level Experts Forum, Rome 13-14 November 2009.

Doberman A. (2003) 'A critical assessment of the system of rice intensification (SRI).'*Agricultural Systems*, 79 (3), 261-281.

EEA (2007) Greenhouse gas emission trends and projections in Europe 2007: Tracking progress towards Kyoto targets Report No 5/2007, European Environment Agency.

EIPRO (2006) *Analysis of the life cycle environmental impacts related to the total final consumption of the EU25*, European Commission Technical Report EUR 22284. Main Report IPTS/ESTP Project. Environmental Impacts of Products.

Ejeta G. (2010) 'Africa's Green Revolution needn't be a mirage.' *Science*, 327, 831-832.

Erb K-H., H. Haberl, F. Krausmann, C. Lauk, C. Plutzar, J.K. Steinberger, C. Müller, A. Bondeau, K. Waha & G. Pollack (2009) *Eating the Planet: Feeding and Fuelling the World Sustainably, Fairly and Humanely – a Scoping Study*. Social Ecology Working Paper 116. Institute of Social Ecology, Vienna.

Evans A. (2009) *The Feeding of the Nine Billion: Global Food Security for the 21st Century*. A Chatham House Report, Royal Institute of International Affairs, London.

Fairlie S. (2009) 'Carbon colonialism and the mathematics of methane. '*The Land,* Issue 8, Winter 2009/10.Chapter 7, Somerset.

Fairlie S. (2007) 'Can Britain Feed Itself?' *The Land*, Issue 4, Winter 2007/08. Chapter 7, Somerset.

FAO (2008^{a}) Investing *in Sustainable Crop Intensification, An International Technical Workshop*. Integrated Crop Management, Volume 6, 2008. FAO, Rome.

FAO (2008) *Climate Change and Food Security, A Framework Document*. FAO, Rome.

FAO (2006) *Livestock's Long Shadow: environmental issues and options*. FAO, Rome.

FAO (2002) *World Agriculture: towards 2015/2030*. FAO, Rome.

Fedoroff, N.V, D. S. Battisti, R. N. Beachy, P. J. M. Cooper, D. A. Fischhoff, C. N. Hodges, V. C. Knauf, D. Lobell, B. J. Mazur, D. Molden, M. P. Reynolds, P. C. Ronald, M. W. Rosegrant, P. A. Sanchez, A. Vonshak, J.-K. Zhu (2010) 'Radically rethinking agriculture for the 21stCentury.'*Science,* 327, 833-834

Fischer G. (2009) 'World Food and Agriculture to 2030/50: How do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability?' Paper presented at the FAO Expert Meeting, 24-26 June 2009, Rome on "How to Feed the World in 2050". FAO, Rome.

FSA (2001) *The Balance of Good Health, Information for Educators and Communicators*. Food Standards Agency, Middlesex.
http://www.food.gov.uk/multimedia/pdfs/publication/boghbooklet0907.pdf

Garnaut R. (2007) *Climate Change Review Report*. Government of Australia.

Garnett T. (2010) *Intensive Versus Extensive Livestock Systems and Greenhouse Gas Emissions.* FCRN Briefing Paper, January 2010. FCRN, Centre for Environmental Strategy, University of Surrey

Garnett T. (2008) *Cooking up a Storm: Food, Greenhouse Gas Emissions and Our Changing Climate*. FCRN, Centre for Environmental Strategy, University of Surrey.

Garnett, T. (2007) *Meat and dairy production & consumption: Exploring the livestock sector's contribution to the UK's greenhouse gas emissions and assessing what less greenhouse gas intensive systems of production and consumption might look like*. FCRN, Centre for Environmental Strategy, University of Surrey.

Garnett, T. (2007 [a]) *Food refrigeration: What is the contribution to greenhouse gas emissions and how might emissions be reduced?* FCRN, Centre for Environmental Strategy, University of Surrey.

Garnett, T. (2006) *The alcohol we drink and its contribution to the UK's greenhouse gas emissions: a discussion paper*. FCRN, Centre for Environmental Strategy, University of Surrey.

Garnett, T. (2006 [a]) *Fruit and vegetables and greenhouse gas emissions: exploring the relationship*, FCRN, Centre for Environmental Strategy, University of Surrey.

Glendining M.J., A.G. Dailey, A.G. Williams, F.K. van Evert, K.W.T. Goulding & A.P. Whitmore (2009) 'Is it possible to increase the sustainability of arable and ruminant agriculture by reducing emissions?' *Agricultural Systems*, 99, 117-125.

Godfray H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas & C. Toulmin (2010). 'Food security: the challenge of feeding 9 billion people.' *Science*, 327, 812-818.

Grace, P.R., Antle, J., Aggarwal, P.K., Andren, O., Ogle, S., Conant, R., Longmire, J., Ashkalov, K., Baethgen, W.E., Valdivia, R. &Paustian, K. (2004) 'Assessment of the Costs and Enhanced Global Potential of Carbon Sequestration in Soil,' *IEA/CON*/03/95.

Golub A., T. Hertel, H.L. Lee, S. Rose & B. Sohngen (2008) *The Opportunity Cost of Land Use and the Global Potential for Greenhouse Gas Mitigation in Agriculture and Forestry*. GTAP Working Paper No. 36. Centre for Global Trade Analysis, Purdue University.

Greenpeace (2008) *New Zealand Farming and Climate Change*. Greenpeace, Auckland.

Gusti M., P. Havlik & M. Obersteiner (2008) *Technical Description of the IIASA Model Cluster.* IIASA

Hall, A. and V. Mogyorody (2001) 'Organic farmers in Ontario: an examination of the conventionalisation argument', *Sociologia Ruralis*, 41 (4): 400-422

Harvey G. (2008). *The Carbon Fields: how our countryside can save Britain*. GrassRoots, Somerset.

Heaps, C., P. Erickson, S. Kartha, & E. Kemp-Benedict (2009) *Europe's share of the climate challenge: Domestic Actions and International Obligations to Protect the Planet,* Stockholm Environment Institute (SEI).

Heinberg R. & M. Bomford (2009) *The Food and Farming Transition: Toward a Post-Carbon Food System*. The Post Carbon Institute, CA.

Holt-Giménez E. (2002) Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. *Agriculture, Ecosystems and Environment*, no 93, pp87-105

HM Treasury (2006) *The Stern Review on the Economics of Climate Change.* HM Treasury, London

Houghton R.A. (2005) 'Tropical deforestation as a source of greenhouse gas emissions', in P. Moutinho & S. Schwartzman (eds): *Tropical Deforestation and Climate Change*. Amazon Institute for Environmental Research.13-22.

IAASTD (2009) *Agriculture at a Crossroads. International Assessment of Agricultural Knowledge, Science and Technology for Development*. Global Report. B.D. McIntyre, .R. Herren, J. Wakhungu & R.T. Watson (eds). Island Press, Washington DC.

IIASA (2009) *A Tool for Comparing Countries' Efforts for Reduced Greenhouse Gas Emissions.* IIASA Policy Brief, 9 December 2009. IIASA, Austria.

ISRIC (2010) *Global Assessment of Land Degradation*. http://www.isric.org/UK/About+ISRIC/Projects/Track+Record/GLASOD.htm website accessed Feb 2010.

IPCC (2007) *Fourth Assessment Report*, Working Group III, Chapter 8.

IPCC (2000) *Emissions Scenarios*, Cambridge University Press.

IPCC (2001) *Climate Change 2001: Mitigation*, Cambridge University Press.

Jackson L.E., U. Pascual & T. Hodgkin (2007). 'Utilizing and conserving agrobiodiversity in agricultural landscapes.' *Agriculture, Ecosystems & Environment* 121, 196-210.

Janzen H.H. (2004) 'Carbon cycling in earth systems – a soil science perspective.' *Agric.Ecosyst. Environ*. 104: 399-47

Jones, C., R. Wilson, & T. Wiley (2008) 'Climate change and the Australian agricultural sector', evidence to the Senate Standing Committee on Rural and Regional Affairs and Transport, Proof Committee Hansard, 30 June, Canberra.

Kartha S., C.K. Siebert, R. Mathur, N. Nakicenovic, V. Ramathan, J. Rockström, H.J. Schellnhuber, L. Srivastava & R. Watt (2009). *A Copenhagen Prognosis: Towards a Safe Climate Future. A Synthesis of the Science of Climate Change, Environment and Development*. Climate Impact Research (PIK), Stockholm Environment Institute (SEI), & Energy and Resources Institute (TERI), Potsdam Institute, Germany.

Khan B.M. & D. Zaks (2009) *Investing In Agriculture: Far-Reaching Challenge, Significant Opportunity*. DB Climate Change Advisors. Deutsche Bank Group.

Keyzer M.A., M.D. Merbis, T.F.P.W. Pavel & C.F.A. Wesenbeeck (2005) 'Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030?' *Ecological Economics*, 55 (2): 187-202

Kongshaug G. (1998) 'Energy consumption and greenhouse gas emissions in fertilizer production. 'Inn *IFA Technical Conference,* Marrakech, Morocco.

Lal R. (2004) 'Carbon emission from farm operations.' *Environment International*, 30: 981-990.

Lee H-L, T.W. Hertel, S. Rose & M. Avetisyan (2007) 'An integrated global land use data base for CGE analysis of climate policy options.' In T. Hertel, S. Rose & R. Tol (eds) *Economic Analysis of Land Use in Global Climate Change Policy*. Routledge.

Lee H-L, T.W. Hertel, B. Sohngen & N. Ramakutty (2005) *Towards an Integrated Land Use Data Base for Assessing the Potential for Greenhouse Gas Mitigation*. GTAP Technical Paper No. 25.Global Trade Analysis Project, Purdue University.

Lehman J. (2007) 'Bio-energy in the black.' *Frontiers in Ecology and Environment*, 5 (7): 381-387.

Lobell D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon & R.L. Naylor (2008). 'Prioritising climate change adaptation needs for food security to 2030.' *Science*, 319: 607-610.

Lotter D.W., R. Seidel & W. Liebhart (2003) The performance of organic and conventional cropping systems in an extreme climate year. *American Journal of Alternative Agriculture,* vol 18, no 3, pp146-154

Lotze-Campen H., C. Müller, A. Bondeau, S. Rost, A. Popp & W. Lucht (2008) 'Global food demand, productivity growth and the scarcity of land and water resources: a spatially explicit mathematical programming approach.' *Agricultural Economics*, 39: 325-338.

Mäder, P. A. Fliessbach, D. Dubois, L. Gunst, P. Fried, & U. Niggli (2002) 'Soil fertility and biodiversity in organic farming', *Science*, 226:1694-1697

McNeeley, J.A. & S. Scherr (2001) *Common Ground, Common Future: How Ecoagriculture Can Help feed the World and Save Wild Biodiversity*. Report No. 5/01, IUCN, Gland

Masui T., Y. Matsuoka & M. Kainuma (undated) *Long-term CO2 Emission Reduction Scenarios in Japan.* http://www.hm-treasury.gov.uk/d/NIES-(2).pdf

Matsuoka, Y. (2005) 'A level of Dangerous Climate Change and Climate Stabilization Target for Developing Long-term Policies', *Environmental Research Quarterly*, 138: 7-16.

Medvedev D., D. van der Mensbrugghe & J. Beghin (2009) *Climate Change and the Future of Global Agriculture.* Development Prospects Group, World Bank. Draft paper.

Metcalf T. & R. Kingwell (2009) 'Low Emission Farming Systems: A Whole-Farm Analysis of the Potential Impacts of Greenhouse Policy.' A contributed paper to the Australian Agricultural & Resource Economics Society's annual conference, Cairns, Feb 11-13, 2009.

Metz B., O. Davidson, H. de Coninck, M. Loos & L. Meyer (2005) *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change IPCC. Cambridge University Press.

Mesure S. (2008) 'The £20 bn food mountain: Britons' throw away half of the food produced each year', *The Independent*, Sunday 2 March.

Midgeley A. & D. Moran (2008) Climate *Change and Agriculture, Selecting the Best Strategy*. Policy Briefing, Rural Policy Centre. Scottish Agricultural College.

Monfreda C., N. Ramankutty & T. Hertel (2007) 'Global agricultural land use data for climate change analysis.' In T. Hertel, S. Rose & R. Tol (eds) *Economic Analysis of Land Use in Global Climate Change Policy*. Routledge.

Mosier A., R. Wassmann, L. Verchot, J. King & C. Palm (2004) 'Methane and nitrogen oxide fluxes in tropical agricultural soils: sources, sinks and mechanisms.' *Environment, Development and Sustainability,* 6: 11-49.

Mosier A. & C. Kroeze (2000) 'Potential impact on the global atmospheric N_2O budget of the increased nitrogen input required to meet future global food demands.' *Chemosphere-Global Change Science*, 2: 456-473.

Mosier A.R., J.M. Duxbury, J.R. Freney, O. Heinemeyer, K. Minami & D.E. Johnson (1998) 'Mitigating agricultural emissions of methane.' *Clim. Change*, 40: 39-80.

Moss R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainum, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, J. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant & T.J. Wilbanks (2010) 'The next generation of scenarios for climate change research and assessment.' *Nature*, 463: 747-756.

Mrini M., F. Senhaji & D. Pimentel (2002).'Energy analysis of sugar beet production under traditional and intensive farming systems and impacts on sustainable agriculture in Morocco.' *Journal of Sustainable Agriculture* 20: 5-28.

Nelson G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Barka, M. Magalhaes, R. Valmonte-Santos, M. Ewing & D. Lee (2009) *Climate Change: Impact on Agriculture and Costs of Adaptation*. Food Policy Report. IFPRI, Washington DC.

Nellemann C., M. MacDevette, T. Manders, B. Eickhout, B. Svihus, A.G. Prins & B.P. Kaltenborn (eds) (2009). *The Environmental Food Crisis*. UNEP, Nairobi.

Neufeldt H. & M. Schäfer (2008) 'Mitigation strategies for greenhouse gas emissions from agriculture using a regional economic-ecosystem model.' *Agriculture, Ecosystems and Environment* 123: 305–316

Nguyen N.V. (undated) *Sustainable Intensification of Rice Production for Food Security in the Near Future – A Summary Report*. International Rice Commission. FAO, Rome.

Niggli U., A. Fließbach, P. Hepperly & N. Scialabba (2009) *Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems*. FAO, April 2009.

Oenema O., N. Wrage, G.L. Velthof, J.W. van Groenigen, J. Dolfing & P.J. Kuikman (2005) 'Trends in global nitrous oxide emissions from animal production systems.' *Nutr.Cucl.Agroecosyt*. 72: 51-65.

Pachauri R.K. & A. Reisinger (eds) (2007) *IPCC Fourth Assessment Report: Climate Change 2007. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland. pp 104

Palm C., T. Tomich, M. van Noordwijk, S. Vosti, J. Gockowski, J. Alegre & L. Verchot (2004) 'Mitigating GHG emissions in the humid tropics: case studies from the alternatives to slash-and-burn program (ASB)'. *Environment, Development and Sustainability*, 6: 145-162.

Parrott, N. and Marsden, T. (2002) *The Real Green Revolution. Organic and Agroecological Farming in the South*. Greenpeace Environmental Trust, London

Parry M.L., C. Rosenzweig, A. Iglesias, M. Livermore & G. Fischer (2004).'Effects of climate change on global food production under SRES emissions and socio-economic scenarios.' *Global Environmental Change*, 14: 53-67.

Paul H., A. Ernsting, S. Semino, S. Gura & A. Lorch (2009).*Agriculture and Climate Change: Real problems, false solutions.* EcoNexus, Oxford.

Paustian K., J.M. Antle, J. Sheehan & E.A. Paul (2006) *Agriculture's Role in Greenhouse Gas Mitigation*. Pew Centre on Global Climate Change, Arlington, VA.

Paustian K., B.A. Babcock J. Hatfield, R. Lal, B.A. McCarl, S. McLaughlin, A. Mosier, C. Rice, G.P. Robertson, N.J. Rosenberg, C. Rosenzweig, W.H. Schlesinger& D. Zilberman (2004).*Agricultural Mitigation of Greenhouse Gases: Science and Policy Options*. CAST (Council on Agricultural Science and Technology) R141.

Pimentel, D. Hepperly, P. Hanson, J. Douds, D. & R. Seidel (2005) 'Environmental, energetic and economic comparisons of organic and conventional farming systems', *Bioscience,* 55(7): 573-582

Pimentel D. & M Pimentel. (2003). 'Sustainability of meat-based and plant based diets and the environment.' *American Journal of Clinical Nutrition* 78,660S-6663.

Pretty J. (2008) 'Agricultural sustainability: concepts, principles and evidence.' *Philosophical Transactions of the Royal Society*, 363: 447-465.

Pretty J.N., A.D. Noble, D. Bossio, J. Dixon. R.E. Hine, F.W.T. Penning de Vries & J.I.L. Morison (2006). 'Resource-Conserving Agriculture Increases Yields in Developing Countries.' *Environmental Science & Technology*, 40 (4) 1114-1119

Pretty J.N, A.S. Ball, L. Xiaoyun & N.H. Ravindranath (2002) 'The role of sustainable agriculture and renewable-resource management in reducing greenhouse-gas emissions and increasing sinks in China and India.' *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 360 (1797): 1741-1761.

Pretty, J.N., J.I.L. Morrison& R.E. Hines (2002[a]) 'Reducing food poverty by increasing agricultural sustainability in developing countries', *Agriculture, Ecosystems and the Environment*, 95: 217-234

Pretty J.N., C. Brett, D. Gee, R.E. Hine, C.F. Mason, J.I.L. Morrison, H. Raven, M. Rayment & G. van de Bijl (2000) 'An assessment of the external costs of UK agriculture', *Agricultural Systems*, 65(2): 113-136.

Pretty, J. and F Shaxson (1997) *The potential of sustainable agriculture*. Paper presented at the DFID Natural Resources Advisers Conferences, 1997. DFID, London

Rundgren, G. (2002) *Organic Agriculture and Food Security*.Dossier 1. IFOAM, Germany

ProAct Network (2008) *The Role of Environmental Management and Eco-Engineering in Disaster Risk Reduction and Climate Change Adaptation. Case Study: Jordan Valley Permaculture Project*. www.proactnetwork.org

Ramírez- Ramírez C.A. (2005) *Monitoring Energy Efficiency in the Food Industry*. PhD thesis. Dept.Science, Technology and Society, Copernicus Institute, Utrecht University.

Ríos H., D. Soleri & D. Cleveland (2001) 'Conceptual changes in Cuban plant breeding in response to a national socioeconomic crisis: the example of pumpkins. *Farmers, Scientists and Plant Breeding, Integrating Knowledge and Practice*.' CABI, Oxon.

Robertson G.P. & P.R. Grace (2004) 'Greenhouse gas fluxes in tropical and temperate agriculture: the need for a full-cost accounting of global warming potentials.' *Environment, Development and Sustainability*, 6: 51-63.

Rose S., S. Finn, E. Scheele, J. Mangino & K. Delhotal (2006) *Detailed Greenhouse Gas Emissions Data for Global Economic Modelling*. US Environmental Protection Agency, Washington DC.

Rosegrant M.W., S. Msangi, T. Sulser & C. Ringler (2007) 'Future Scenarios for Agriculture: Plausible Futures to 2030 and Key Trends in Agricultural Growth.' Background paper prepared for the *World Development Report 2008.*

Roshetko J.M., M. Delaney, K. Hairiah & P. Purnomosidhi (2002) Carbon stocks in Indonesian homegarden systems: Can smallholder systems be targeted for increased carbon storage? *American Journal of Alternative Agriculture* 17: 138-148.

RSA (2009) *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture*. Royal Society, London.

Sanchez P.A. (2002) Soil fertility and hunger in Africa. *Science* 295: 2019-2020.

Savory A. (1999) *Holistic Management: A New Framework for Decision Making*. Island Press, Washington DC.

Saunders C. & A. Barber (2007) *Comparative Energy and Greenhouse Gas Emissions of New Zealand's and the UK's Dairy Industry*. Research Report No. 297. Lincoln University, New Zealand.

Scherr S.J. & S. Sthapit (2009) Mitigating *Climate Change through Food and Land Use*. Worldwatch Report 179. Worldwatch Institute, Washington DC.

Schmidhuber J. & F.N. Tubiello (2009) 'Global food security under climate change.' P*NASS*, 104(50): 19703-19708.

Scialabba, N. E. & C. Hattam (2002) *Organic Agriculture, Environment and Food Security.* Environment and Natural Resources Series 4. FAO, Rome

Smith P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenk, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider, S. Towprayoon, M. Wattenbach & J. Smith. (2008) 'Greenhouse Gas Emissions in Agriculture.' *Philosophical Transactions of the Royal Society B*. London.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko (2007) 'Agriculture.' In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Smith P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenk, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider & S.Towprayoon (2007) 'Policy and technological constraints to implementation of greenhouse gas emissions in agriculture.' *Agriculture, Ecosystems and Environment*, 118: 6-28.

Smith P. (2004) 'Engineered biological sinks on land.' In: Field C.B. & M.R. Raupach (eds) *Integrating Humans, Climate and the Natural World*. Island Press, Washington DC.p479-491.

Smith P., D.S. Powlson, J.U. Smith, P. Falloon & K. Coleman (2000) 'Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture.' *Global Change Biology*, 6: 525-539

Smith K.A. & F. Conen (2004). 'Impacts of land management on fluxes of trace greenhouse gases.' *Soil Use Management*, 20: 255-263

Srinivasan C.S., X. Irz & B. Shankar (2006) ‘An assessment of the potential consumption impacts of WHO dietary norms in OECD countries.’ *Food Policy* 31: 53-77.

Stanton E.A. & F. Ackerman (2009) *Climate and Development Economics: Balancing Science, Politics and Equity.* Working Paper WP-US- 0908. Stockholm Environment Institute, Stockholm

Stehfest E., L. Bouwman, D.P. van Vuuren, M.G.J. den Elzen, B. Eickhout & P. Kabat. (2009) ‘Climate benefits of a changing diet. *‘Climate Change*. DOI 10.1007/s10584-008-9534-6 Published online.

Stuart T. (2009) *Uncovering the Global Food Scandal*. Penguin, London.

Tubiello F., J. Schmidhuber, M. Howden, P.G. Neofotis, S. Park, E. Fernandes & D. Thapa (2008) *Climate Change Response Strategies for Agriculture: Challenges and Opportunities for the 21st Century*. Agriculture and Rural Development Discussion Paper 42.The World Bank, Washington DC.

Tubiello F.N. & C. Rosenzweig (2008) ‘Agricultural Impact Metrics to Assess the Benefits of Climate Policies.’ *Journal of Integrated Assessment*, 8 (1): 165-184.

US-EPA (2006) *Global Anthropogenic non-CO2 Greenhouse Gas Emissions, 1990-2020*.United State Environment Protection Agency EPA 430-R-06-005, Washington DC.

Vlek P.L.G., G. Rodríguez-Kuhl & R. Sommer (2004) ‘Energy use and CO_2 Production in Tropical Agriculture and Means and Strategies for Reduction or Mitigation.’ *Environment, Development and Sustainability*, 6: 213-233.

Wassmann R., H.U. Neue, J.K. Ladha & M.S. Aulakh (2004) ‘Mitigating greenhouse gas emissions from rice-wheat cropping systems in Asia.’ *Environment, Development and Sustainability*, 6:65-90.

Weyant J.P., F.C. de la Chesnaye & G.J. Blanford (2006). ‘Overview of EMF21: Multigas Mitigation and Climate Policy.’ In: de la Chesnaye, F.C. and J.P. Weyant (eds.), 2006: Multi-gas mitigation and climate policy. *The Energy Journal*, Special Issue No.3, 520 pp.

WFP (2009) *Climate Change and Hunger: Responding to the Challenge*. World Food Programme, Rome.

WHO (2006) *Overweight and Obesity*. Factsheet no 311. September 2006. http://www.who.int/mediacentre/factsheets/fs311/en/index.html

WHO (2003) *Diet, Nutrition and the Prevention of Chronic Disease*. Report of the joint WHO/FAO expert consultation. WHO Technical Report Series, No. 916.

World Bank (2008) *Agriculture for Development*. World Bank Development Report. World Bank, Washington DC.

WRAP (2008) *The Food We Waste*. Waste and Resources Action Programme, Banbury.

Wright J. (2009) *Sustainable Agriculture and Food Security in an Era of Oil Scarcity*. Earthscan Publications

Wright S. (2002) *Glomalin: Hiding Place for a Third of the World’s Stored Soil Carbon*. Agricultural Research, September 2002.

Ziesemer, J. (2008) *Energy Use in Organic Food Systems*. FAO, Rome. 28p.

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