University of Southampton
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The Suitability of Anaerobic Digesters on Organic Farms

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Abstract

Food and energy security are two key environmental challenges currently faced by mankind. The principles behind organic farming are to promote environmental sustainability; however within the organic standards the use of renewable energy is only a suggested method with which to achieve this. If organic farmers can successfully utilise anaerobic digesters, they could contribute towards the provision of both food and energy security using one holistic system. Within this thesis, the suitability of anaerobic digesters on organic farms was explored using methods from ecological, sociological and environmental sciences. This enabled both the practical and theoretical issues behind the question of whether it is suitable for anaerobic digesters to be used on organic farms to be addressed.

Field and laboratory experiments were used to compare the effects digestate and slurry had on earthworms, grass and weeds. Digestate and slurry had species dependent effects on earthworms during both LD_{50} / LT_{50} experiments and behavioural bioassays; *Lumbricus terrestris* survived longer in slurry and showed a behavioural preference towards slurry over digestate, whereas *Eisenia fetida* showed the opposite responses. Fertiliser application rates over 170 kg N ha^{-1} were found to be harmful to both species of earthworm. Suppressed germination effects were seen on thistles treated with digestate compared with no treatment ($F_{0.56,19.66}$ =4.66, $P < 0.01$), whilst grass fertilised with digestate had a greater total mass than grass fertilised with slurry or left unfertilised ($F_{2,27}$ =17.92, $P < 0.001$).
Questionnaires and interviews were used to obtain a better understanding of the opinions farmers had about anaerobic digesters. Organic farmers believed renewable energy generation fitted well within organic principles, but using an anaerobic digester on an organic farm was less practical than on a conventional farm. This was due to multiple reasons including lack of information, poor associated finances, and that existing digesters are currently unsuitable for small organic farms. There was also support for anaerobic digesters to be on dairy farms- this was regardless of whether the farm was organic or conventional.

Two case-study farms were used to assess the impact an anaerobic digester would have on the farms total GHG emissions. An anaerobic digester on the dairy farm was calculated to reduce GHG emissions by up to 24%, while for the mixed farm, the maximum reduction was by 20%. This was primarily due to the fact that the dairy farm benefitted from a higher volume of feedstock and proposed to use the biogas in a more energy efficient manner by producing electricity rather than vehicle fuel. Due to the high emissions associated with keeping livestock, both case studies needed to import additional feedstock if the farms were to achieve zero net GHG emissions.

The answer to whether anaerobic digesters can be suitable for organic farms was judged on how well they complimented or conflicted with IFOAM's definition of organic farming. Three main aspects of their definition were chosen and evidence from each chapter used to address the main question of the thesis. In conclusion, anaerobic digesters are theoretically suitable for use on organic farms, but are

generally more practical for use on conventional farm systems. Across both farm systems the most suitable enterprises to adopt anaerobic digesters are dairy farms. This highlights the need for suitability of new systems to be assessed on a case-by-case scenario when trying to maximise positive impacts from new technologies.

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Abbreviations

ADTG	Anaerobic Digestion Task Group
ABT	Avoidance Behaviour Test
CO_2	Carbon dioxide
CO_2 equiv.	Carbon dioxide equivalent
CHP	Combined Heat and Power
CLA	Country Land and Business Association
DECC	Department of Energy and Climate Change
DEFRA	Department of Environment, Food and Rural affairs
EC50	Effective Concentration 50
ESRC	Economic and Social Research Council
ELS	Entry Level Stewardship
EA	Environment Agency
EPA	Environmental Protection Agency
ECR	Environmentally Controlled Room
EC	European Council
EEA	European Environment Agency
EU	European Union
FIT	Feed in Tariff
GM	Genetically Modified
GJ	Gigajoules
GHG	Greenhouse Gas
GHG's	Greenhouse Gases
GWP	Greenhouse Warming Potential
Ha	Hectares
IGER	Institute of Grassland and Environmental Research
IPCC	Intergovernmental Panel on Climate Change
IFOAM	International Federation of Organic Agriculture Movement
ISO	International Organization for Standardization
kWh	Kilowatt hour
kW	kilowatts

LD_{50}	Lethal Dose 50
LT_{50}	Lethal Time 50
LW	Live Weight
CH_4	Methane
NFU	National Farmers Union
NNFCC	National Non-Food Crops Centre
NVZ's	Nitrogen Vulnerable Zone's
OELS	Organic Entry Level Stewardship
OM	Organic Matter
RE	Renewable energy
REA	Renewable Energy Association
RHI	Renewable Heat Incentive
ROC's	Renewable Obligations Certificates
RASE	Royal Agricultural Society of England
RELU	Rural Economy and Land Use Programme
SRC	Short Rotation Coppice
SA	Soil Association
TKN	Total Kjeldahl Nitrogen
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
UoR	University of Reading
UoS	University of Southampton
VOC	Volatile Organic Compound
WHC	Water Holding Capacity
WRAP	Waste and Resource Action Programme

Declaration of Authorship

I, Laura Clements, declare that the thesis entitled "The suitability of anaerobic digesters for organic farming systems" and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at the University of Southampton;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

Signed:

Date:

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Chapter 1

General Introduction

1.1 Issues around environmental sustainability

One of the key challenges facing the world is the increasing demand for energy, driven by an expanding global population combined with widespread industrialisation. Prof. Sir John Beddington, the former chief scientific advisor to the UK government, predicted that by 2030 we will require 50% more energy, as well as 50% more food and 30% more fresh water than is currently available (Beddington 2010, Godfray *et al.* 2010). Moreover, increased energy usage has resulted in higher emissions of greenhouse gases (GHGs), a key driver of climate change; with world emissions rising by 70% between 1970 and 2004 (IPCC Assessment Report 3, 2007). Climate change in turn, is interlinked with many other global issues, such as food security. The United Nations Framework Convention on Climate Change (UNFCCC) has set targets for countries to meet via the Kyoto Protocol (United Nations 1998) with a call for national policies covering topics such as: energy efficiency; promoting sustainable agriculture; research, promoting and developing renewable energies; measuring and reducing GHG emissions, and limiting methane emissions. Since the Kyoto Protocol, this has been followed by the United Nations Conference on Sustainable Development, or Rio +20. Through this, a set of Sustainable Development Goals (SDGs) were created and built upon the Millennium Development Goals. The Conference further considered issues relating to a number of thematic areas, including energy, food security, sustainable consumption and production, and biodiversity and ecosystems (United Nations 2008).

One way of addressing the world's increased demand for energy, whilst mitigating climate change, is to generate energy from renewable sources and replace non-renewable sources that are responsible for the release of GHG's. Anaerobic digestion technology can generate renewable energy and contribute to reducing pollution associated with waste management, which currently is responsible for around 10% of the emissions released in agriculture (Sommer & Olesen 2000, Svensson & Pell 2001). Anaerobic digesters facilitate the fermentation of organic material by capturing methane released in a controlled environment. For example, anaerobic digesters located on farms can reduce emissions from agricultural waste and divert waste from landfill. They can also generate biogas, a renewable energy source, which can be used to help meet the energy needs of the farm. Finally, the solid residuals left after fermentation can be recycled back to the land, reducing pollution and the need for synthetic fertilisers. Agriculture is one of the largest industrial contributors to GHG emissions, both globally and in the UK (IPCC 2006, DECC 2011d). Anaerobic digestion technology, coupled with other sustainable agricultural practices may be a useful mechanism to reduce the impact that farming has upon climate change (Johnson *et al.* 2007).

1.2 Anaerobic digestion and anaerobic digesters

Anaerobic digestion is not a new method of generating energy. Developing countries have been using anaerobic digesters for waste management and for producing cooking and lighting fuel since the 19th century. The first recorded anaerobic digester was in Bombay in 1859, with farm-scale digesters developed in Kenya and South Africa during the 1950's (Meynell 1982). Currently China has over 7.5 million household biogas digesters and India over three million (Muller 2007). In addition, China has 750 large and medium scale digesters (Lansing *et al.* 2008, Ferrer *et al.* 2009). Within Europe, electricity generation from biogas has increased on average by 19% per year between 1997 and 2006 from 3.49 to 17.30 terawatt hours (TWh) (Coenraads *et al.* 2008). Producing biogas has long been established in Britain, although this is mainly from sewage works (Meynell 1982, Carruthers & Jones 1983). The UK produces the most biogas from sewage works, although Germany is now the largest producer of biogas within the EU (EurObserv-ER 2012). In the UK, there are currently 146 sewage plants, with 66% of these treating sludge by anaerobic digestion (EA 2011, NNFCC 2011). Anaerobic digesters on farms are relatively rare, with only 0.01% of farms owning a digester. In the UK (Banks *et al.,* 2006), this represents just 29 sites using farm feedstock digesters (NNFCC, 2011). In Europe anaerobic digesters have been established for longer and on a larger scale (Banks *et al.* 2007). Germany are the leaders in implementing anaerobic digestion in agriculture and together by 2005 they had over 1900 on-farm anaerobic digester plants (AD-Nett 2005b).

1.2.1 How anaerobic digesters work

Anaerobic digestion is the breakdown of organic materials (feedstock) in anaerobic conditions to produce two usable products; biogas and digestate. This is done through a controlled process within an anaerobic digester. It involves a multi-stage bacterial process to break down carbohydrates, fats and proteins into methane and carbon dioxide (Figure 1.1).

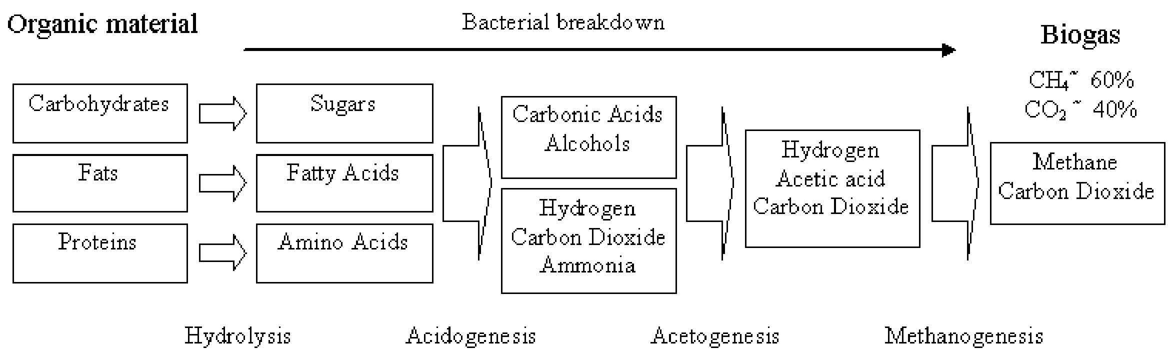


Figure 1.1. The four stage bacteria-driven chemical process of anaerobic digestion, from organic material to biogas. Digestate is also produced as a bi-product, not drawn here. (Adapted from (Hall & Howe 2012)).

The gas composition of biogas ranges from 30 - 45% carbon dioxide and 55 - 75% methane, with traces of other gases such as hydrogen sulphide, nitrogen, hydrogen, carbon monoxide and oxygen (Igoni *et al.* 2008). The breakdown is explained by Buswell's formula:

$$[C_nH_aO_b + {}_{(n\text{-}a/4 - b/2)}\, H_2O = ({}_{n/2 - a/8 + b/4})\, C0_2 + CH_4]$$

(Symons & Buswell 1933).

The percentage volume of each of the gases produced are dependent on the type of feedstock used (NNFCC 2011). Better digestion is achieved by mixing types of feedstock (co-digestion), compared with using a single feedstock (Weiland 2000). Feedstock such as food waste can produce 156 m^3 of biogas per tonne (Banks *et al.* 2011b), while other feedstock, such as manures, produce only 15 - 25 m^3 of biogas per tonne (NNFCC 2011). Other factors that affect gas volume include temperature, retention time, loading rate, the type of bacteria present and the pH of the digestate in the anaerobic digester (Garcia 2005, Schittenhelm 2008).

The biogas produced can be used to generate power and replace fossil fuel-derived energy (Figure 1.2). The simplest use of biogas is to burn it in a boiler to produce heat. This can be used to heat buildings, water or to cook food. Biogas can also generate electricity through using a Combined Heat and Power (CHP) unit. The efficiency of this process varies depending on the equipment used, but the norm is 35% (Banks 2009, Salter 2011). As heat is also produced by CHP, the full benefit of the system can only be achieved where there is an on-site use for the heat. Biogas can also be compressed or upgraded to bio-methane by stripping out the sulphur and removing the carbon dioxide. The product can then replace the natural gas used in modified natural gas powered vehicles.

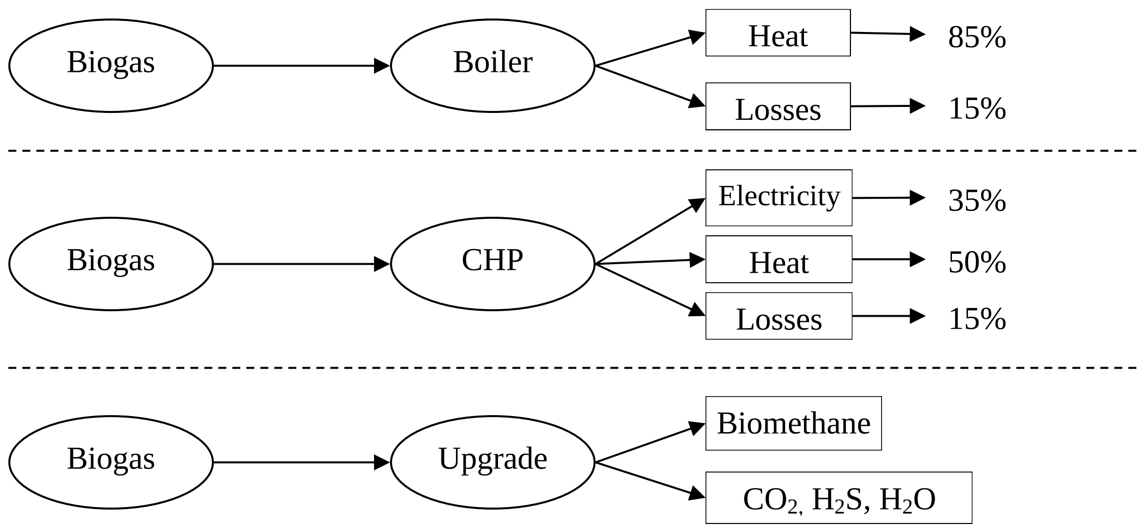


Figure 1.2. Three potential uses for biogas within a farm system. Percentage efficiencies differ depending on the type of machinery used (adapted from Banks 2009).

In addition to biogas, a second product is produced called digestate. This is the residual organic material left over from the digestion process. Digestate has both chemical and physical changes compared to the original feedstock, although many of the key nutrients required for agricultural use remain unchanged (Banks *et al.* 2011a). The digestate has a lower organic matter (OM) content than the feedstock but it has a better balance between the carbon to nitrogen content required for plant growth (Moller 2009). There is also an increase in the pH and ammoniacal content of the material after digestion (Wulf *et al.* 2002a, Clemens *et al.* 2006, Ernst *et al.* 2008a). In this form, nutrients are more readily available to plants, although this does mean there are less available for soil microbes to feed on (Ernst *et al.* 2008a).

1.2.2 How can anaerobic digesters contribute towards international and national targets?

Anaerobic digestion could be used to help achieve international and national targets identified within environmental priority areas outlined by the 6th Environmental Action Programme (EAP) (EC 2002). This includes reducing GHG emissions from agriculture. Agriculture is the 4th largest emitter of GHGs, and is responsible for 8.8% of the total emissions in the UK (DECC 2010). It is the second largest emitter of methane (38% of UK total, after landfill) and the largest emitter of nitrous oxide (76% of UK total) (DECC 2010). Some 5 - 30% of agricultural emissions arise from the management of manure (Sommer & Olesen 2000, Svensson & Pell 2001); with the majority through livestock digestion of food (enteric fermentation) (Figure 1.3). By treating farm manures in an anaerobic digester, farmers can reduce the total GHG emissions associated with their farm in three ways; by improving waste management, by replacing fossil fuel derived energy sources with renewable alternatives, and by recycling nutrients back to the land.

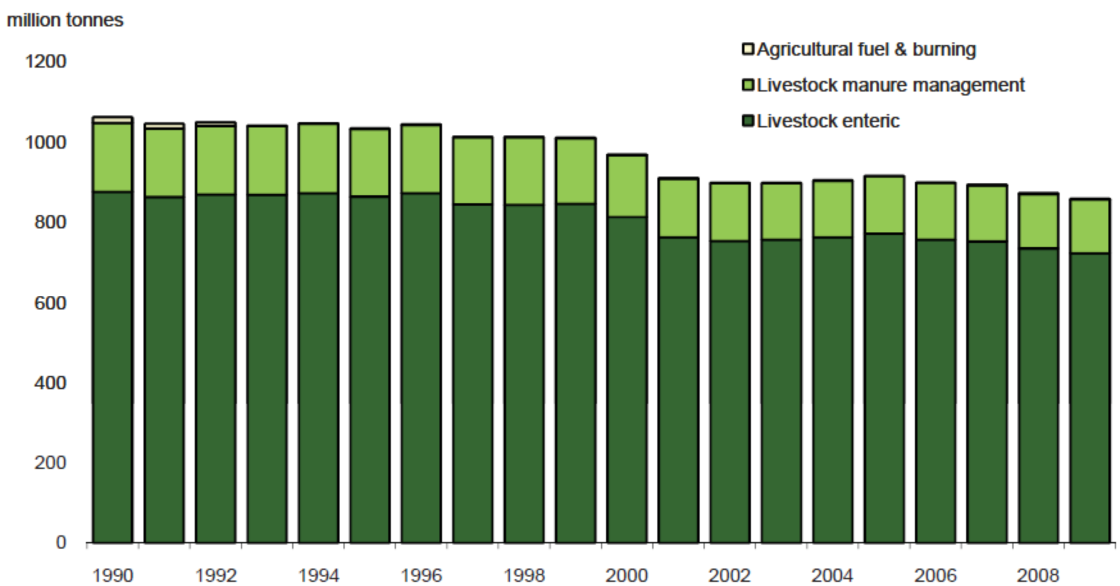


Figure 1.3. Methane emissions by source between 1990- 2009 for the UK. The overall fall in methane emissions has mainly been due to decreasing livestock numbers, rather than changes in practice (taken from DEFRA 2010b).

i) Improving waste management

According to the European Topic Centre on Sustainable Consumption and Production, waste is defined as:

“all items that people no longer have any use for, which they either intend to get rid of or have already discarded” (EEA 2009).

In 2007, the UK produced 8.3 million tonnes of food waste, with the majority of it going to landfill (Quested & Johnson 2009). Some of the 28.6 million tonnes of CO_2 could be avoided if food waste was diverted from landfill, and treated in anaerobic digesters on farms (Quested & Johnson 2009), with the digestate being used as a fertiliser. As a result, the EAP now consider improving waste management as an important issue to be achieved through the *Natural resources and waste* priority action area (EC 2002). Using anaerobic digesters to treat waste could help to achieve international targets set out in; the Waste Framework Directive (2008/98/EC) and the Landfill Directive (1999/31/EC), aid with the Waste Prevention Communication (2005, sections 666 & 667) and also contribute towards national policy outlined in the Waste Strategy 2007. Utilising farm- based sites would be one of the main methods by which this can be achieved.

Although treating waste through anaerobic digesters can reduce degradation emissions, the digestate may still be considered a waste product and will have to be disposed of appropriately. To allow farmers permission to spread anaerobically digested residuals back on to the land, the material must comply with the Quality Protocol and PAS110 (WRAP 2008). These outline the minimum quality of the digestate before it is allowed to be used as a fertiliser. By following these guidelines, material once considered waste can be re-categorised as having fertiliser value. This in turn reduces the amount sent to landfill. Currently anaerobic digestion recovery is considered the only technology enabling the recovery of waste products (Braber 1995, Banks *et al.* 2007, NNFCC 2011).

Farm created materials, such as animal faeces and non-hazardous materials, are excluded from the Waste Framework Directive (2008/98/EC) under Article 2, sections 1f, 2b and 2c. They are not considered “waste” and are excluded from the regulations associated with waste management for digestate. However, where farmers use a combination of animal wastes and food waste within a digester, that digestate would be considered a waste. They would therefore be subject to the Waste Framework Directive. As this thesis focuses mainly on farm based systems, and in particular organic farms (see section 1.1.3 below), the discussion of treating waste is of limited importance for this study.

ii) Energy supply

Anaerobic digestion technology can contribute towards multiple international targets associated with increasing renewable energy generation. Within the Directive 2009/28/EC, the European Council (EC) has set down objectives to achieve 21% of electricity generation from renewable sources. Anaerobic digesters can also be used to contribute towards achieving targets set out in the Directive (2003/30/EC) to promote biofuels, which aims for member states to achieve a minimum share of 5.75% of the biofuel market. Finally, anaerobic digestion can offer a secure energy supply, sustainable development and a competitive market for generating both electricity and fuels through the Biomass Action Programme (COM (2005) 628). Within the UK, The Renewable Energy Action Plan (DECC 2009a) has set targets for 15% of the UK's gross final consumption of energy to be derived from renewable energy by 2020. Within this, different energy forms each have their own targets. These targets are 30% of the UK's electricity source, 12% of its heat and 10% of its transport fuels. Biogas can be used to generate energy in all of these forms and therefore is a highly versatile option that should be further utilised.

Financial support to generate renewable energy is available from the UK government through the Renewable Obligation Certificates (ROC's), Feed-in-Tariff's (FIT's) and the Renewable Heat Incentives (RHI's). Anaerobic digesters can qualify for all of these sources of revenue (see section 1.4.3 below). Currently Feed-in-Tariffs (FIT's) of 14p kWh^{-1} are available for plants generating <250 kW, and 13 p kWh^{-1} for plants between 250 - 250kW, both of which are guaranteed for 20 years (DECC 2011b). This financial support may encourage farmers to build digesters larger than required for their own farm systems, allowing them to import and treat other streams of organic material, such as food waste or green wastes. This means they are able to generate more biogas and more profits. Despite this support, in 2005 the UK's gross final energy consumption from renewables was just 1.4%, and by 2010 it was only 3.3% (DECC 2011d). Consequently, there is a long way to go to reach the 15% target by 2020 and with only 29 anaerobic digesters based on farm feedstock, there is room for improvement within this sector (DECC 2011b, NNFCC 2011).

iii) Recycling digestate back to land

Good nutrient management techniques require the farmer to match the fertiliser nutrient value with the demands of the crop (DEFRA 2009d). Digestate has been found to contain similar nutrients to those which are contained within the original feedstock (Banks *et al.* 2011a, Seadi & Lukehurst 2012). Thus if a farmer recycles the digestate back onto the fields from which the digester feedstock was obtained, the nutrient value of the digestate should match the demands of the crop (Banks *et al.* 2011a). This could work well where a farmer is growing energy crops specifically to feed the digester. Energy crops often have high methane yields which can maximise biogas production (NNFCC 2011). Indeed, some farmers feed their anaerobic digester systems predominantly on high methane yielding crops, like maize as this has a methane potential of 560 $m^3 t^{-1}$ (NNFCC 2011).

Anaerobic digestion can also contribute towards the EU's Nitrates Directive (91/676/EEC) by regulating the application of nitrates applied to soils. Excess nitrates that leach into waterways create pollution and can cause eutrophication (DEFRA 2009c). Lands that drain into a water course are now designated to be within a Nitrogen Vulnerable Zone (NVZ). Currently 62% of the land in England is designated as an NVZ (DEFRA 2011b). As a result, farmers are now restricted to an average nitrogen spread across the farm of 170 kg N ha^{-1} (EC 1991). In addition the Nitrates Directive's tighter regulations limit the storage of manures and slurries, and the dates and conditions when they can be applied to land. This has meant that many farmers have had to increase their storage capacity in order to comply. Anaerobic digesters can create a controlled environment where manures can be stored, offering farmers an alternative manure management strategy and helping to deliver the objectives of the Nitrates Directive. As the digestion process reduces the material's total OM content, the amount of materials requiring storage also reduces. Additionally, the increase ratio of inorganic nitrogen from organic nitrogen enables plants to take up the nitrogen more rapidly, thereby reducing the risk of leaching (Ernst *et al.* 2008b, Moller 2009)

1.2.3 Anaerobic digesters within agriculture and the boundaries of this thesis

Anaerobic digesters can be used in a wide range of industrial settings to treat a variety of organic materials. Such a broad analysis is beyond the scope of this study. Here, anaerobic digesters are assessed to determine whether they can be used as a complimentary tool for organic farms. Any farming practices that use anaerobic digester systems as an industrial process to treat municipal or food waste products are excluded from this study. The adoption of anaerobic digesters has led some farmers in Europe to move from being food producers to energy producers (Weiland 2000, Banks *et al.* 2007); such examples are also excluded as they do not address food security issues as outlined in the EAP (EC 2002). Some of the chapters discuss the potential of farmers incorporating food waste in addition to their farm sourced feedstock materials, although current organic certification regulations may not allow this. This is primarily because of the fear of Genetically Modified (GM) food contamination (Soil Association 2008). By excluding food waste feedstock from this report; the consideration of waste legislation and treatment; associated financial topics; feedstock sourcing options; some planning opposition; as well as many other issues, can be bypassed. The focus here is self-sourced, farm-based anaerobic digesters.

1.3 Sustainable farming

The unsustainable way humans manage their natural resources was brought to world leaders' attention through the first United Nations Rio Summit in 1992. Since then methods to reduce humans' effects on the environment have been explored. More recently, the concept of ecosystem services has been developed to aid our understanding of how we manage natural resources (MEA 2005), and how we value services (TEEB 2013). Ecosystem services are the benefits which people receive from the ecosystem(MEA 2005, NEA 2011)). These include regulating services; such as flood and disease control, provisioning services; such as water and air, supporting services; such as the nutrient cycles, and cultural services, such as spiritual or recreational benefits (UK NEA 2011; (Power 2010)) . Many agricultural processes are dependent on ecosystem services (Power 2010). For example, soil species are critical for facilitating the breakdown of organic matter and release of organic nutrients back into the soil. Without these, farms using organic fertilisers may struggle to maintain the soil's fertility. It is therefore important to protect these ecosystems and the services they provide if mankind is to continue to produce a sustainable amount of food and fuel (Power 2010, NEA 2011).

The Oxford dictionary's definition of sustainable is; *Conserving an ecological balance by avoiding depletion of natural resources* (OED 2013). The WHO define food security as *"when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life"* and is only possible if production is sustainable; accessible and used appropriately (WHO 2013). There are many different agricultural methods used to try a farm agricultural land sustainably. Using less pesticides and synthetic fertilisers are just two methods. Pesticides were first used to increase the production of food in order to feed the growing population. Their toxic effects have been widely investigated, and are known to cause water pollution (De Lorenzo *et al.* 2001), kill non-target species (Santos *et al.* 2012, Farooqui 2013), cause ecological imbalances and destroying useful plants (Power *et al.* 2013)). High pesticide use can be replaced by using integrated pest management, for example, using biological control which works with natural communities within the ecosystem, or by carefully timing the pesticide application (Dent 1995).

Synthetic fertilisers are energy intensive to produce and transport, resulting in high GHG emissions (Lal 2004, Berglund & Börjesson 2006). The two key nutrients for chemical fertilisers are nitrogen and phosphate. Although nitrogen is readily available in the atmosphere, its conversion into a suitable fertiliser product is very energy demanding. For example, the production of 1000 g of ammonium nitrate fertiliser in the UK, releases the equivalent of 2189.8 g of carbon dioxide (CO_2 equiv.) Phosphate also has an energy cost; with one tonne of phosphate fertiliser in Europe producing 520 g CO_2 equiv. (Davis & Haglund 1999, Mader *et al.* 2002, Elsayed *et al.* 2003). Sourcing phosphate is a larger issue than its CO_2 equiv. debt. The availability of phosphate is currently a worldwide concern; as stocks get lower mining phosphate rock becomes more difficult and costly (Cordell *et al.* 2009, Morrigan 2010). As a result, the demand and price for phosphate rock has increased since October 2006 from £39 t^{-1}, to £126 t^{-1} in October 2011, with a peak in October 2008 of £245 t^{-1} (World Bank 2011). Using organic fertilisers is one alternative method of fertilising fields while avoiding the energy costs associated with synthetic fertilisers (Azeez & Hewlett 2008).

Natural England incentivises farmers using methods that are considered to be sustainable through agri-environmental schemes. These include; using grass buffer strips in arable fields by waterways to reduce soil erosion and water pollution, or to support regulatory ecosystems through the increase of plant biodiversity and promotion of pollinators (Natural England 2010). As of 2010 over 66% of UK agricultural land was involved within an agri-environmental scheme. Early calculations also suggest that AES currently deliver a GHG saving of 3.46 million tonnes of CO2 equivalent per year. This is an 11% reduction from the agriculture, forestry and land management sector in England (Natural England 2010).

Sustainable intensification (SI) promotes the use of sustainable agricultural methods with the purpose of globally increasing food supply without using more land, while diminishing the impact on the environment (Royal Society, 2009; Foresight, 2011; Firbank, 2012). Methods used within SI farming discourage the use of unnecessary external products, minimise the use of technologies or practices that have adverse impacts on the environment, harness agro-ecological processes such as nutrient cycling and natural food webs, and utilise crops and animal breeds with high yields (Society. 2009, Godfray *et al.* 2010). These methods enable food security in areas where access to food is low.

1.3.1 Organic farming

Organic farming is another system whereby farmers attempt to farm more sustainably and uses similar methods as SI farming. Agricultural methods used by organic farming have been used for centuries (Blake 1990, Lampkin *et al.* 2008) and may provide a model of good practice to reduce the environmental impact of agriculture (Tuomisto *et al.* 2012). Unlike SI, organic farming does not try to maximise crop yield, with many organic crops unable to achieve such high yields as other farming methods (Rahmann *et al.* 2009, Arncken *et al.* 2012, Seufert *et al.* 2012). Organic farming therefore may not offer the same opportunities for food security as SI. To be classified as an organic farm, certification must come from a registered organic organisation. Organic farming is therefore a trademark whereby farmers must abide by strict standards in order to remain organic. The International Federation of Organic Agriculture Movement (IFOAM) is the umbrella organisation for organic farming, and considers it to be:

"… a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved". (IFOAM 2008)

IFOAM is also the organisation responsible for generating the basic principles. From these, national UK groups, including the Soil Association and Organic Farmers and Growers, create standards which farmers must meet in order to qualify for organic status.

Although standards may differ between certifying bodies, they share the overarching aim for organic farming to protect the soil by maximise recycling, reuse and reduce the amount of external resources required. Soil fertility is managed through crop rotations, growing green manures and recycling organic materials back to land (Blake 1990, Lampkin *et al.* 2008). To release the nutrients, organic farmers rely upon the degradation of organic matter facilitated by soil based cycles. Soil species are critically important for the regulation of soil based ecosystem processes (Power 2010). As a result, organic farming is often based on the philosophy of a holistic system, and technologies and practices which promote this are encouraged. Therefore using an anaerobic digester to treat waste, generate energy for use on the farm and to replace fossil fuel sources aligns with the philosophy of organic farming (Johnson *et al.* 2007).

1.3.2 Anaerobic digesters on organic farms

If a new technology is to be permitted on organic farms, it must meet the strict organic standards. As yet, no research has been conducted on whether anaerobic digesters are suitable for organic farms. For this thesis, areas have been identified where using an anaerobic digester may cause conflict or may further compliment organic principles than existing methods. These have been separated into four areas of research, comprising the four chapters of the thesis. The concluding general discussion uses data from each of the components to assess to what degree anaerobic digesters fit within the IFOAM's definition of organic farms.

i) Fertilising properties of digestate

Organic farmers already treat and recycle organic manures back to land and aim to farm as sustainably as possible. Because anaerobic digestion offers additional benefits to simple composting (Clemens & Ahlgrimm 2001, Sandars *et al.* 2003, Yiridoe *et al.* 2009), the technology may appeal to organic farmers.

Any increased use of anaerobic digesters (Banks *et al.* 2011b, Tranter *et al.* 2011) is likely to increase digestate production and the need for its disposal (DEFRA 2010a). While many of the properties of digestate remain similar to those of its original feedstock, especially its nutrient content, some properties do change, for example, the form in which the nitrogen is held, the percentage of organic matter remaining and the pH value. These changes are likely to cause the digestate to act differently as a fertiliser, compared with its original feedstock. This variation may be particularly important if it affects the growth of grass, as farms using digestate are likely to have grazing livestock. To date, digestate has been shown to increase growth in multiple crops, for example, watermelons (Alburquerque et al., 2010) and lettuce (Montemurro et al., 2010). Although there are few peer reviewed papers on digestate quality, there is on-going research by WRAP in their *Digestate and Compost in Agriculture Project* (Project Code: OMK001-001).

The digestion process has been found to kill seeds that enter the anaerobic digester (Engeli *et al.* 1993, Westerman *et al.* 2012). This means weeds are not reintroduced to fields when the digestate is spread. Currently, little work has been done on the impact digestate could have on weeds already existing within the field. Weed control in organic farms is generally mechanical and time consuming (Bilalis *et al.* 2003, Mace *et al.* 2007); consequently there is a need to investigate what potential impact digestate use might have on weed control. Any reduction in the number of emerging weeds could have a positive impact on organic farming. Alternatively, digestate may increase weed growth, creating competition with crops and more work for farmers.

Crop growth in Italian Ryegrass (due to its common use on dairy farms) and weeds (thistles and brambles often found in organic fields) are studied within chapter two to understand the fertilising potential of digestate.

ii) The ecological effects of using digestate as a fertiliser

The chemical changes in digestate compared with the original feedstock could have an impact on key soil biota. Earthworms, for example, play an important role within the soil as they contribute to the soil’s chemical, physical and biological value (Edwards & Lofty 1972) and as a result offer an excellent model species with which to explore the effects of digestate. It is unclear what effect digestate has on earthworms. One study has shown that at low concentrations, digestate does not affect earthworm mortality but may decrease biomass (Brauckmann & Broll 2007), while a second study found no significant difference between manure and digestate treatments for earthworm numbers and biomass (Bermejo *et al.* 2010). Understanding the ecological effects digestate has on soil biota is therefore important

Understanding the effects digestate has on earthworms could be crucial for organic farmers. Digestate contains high levels of ammonia, which at high concentrations is known to impact negatively on earthworm populations (Edwards & Lofty 1972, Cotton & Curry 1980). Digestate is also lower in OM than its original feedstock and therefore these two changes may have important impacts on earthworm communities. This is explored in chapters two and three.

Many earthworm laboratory trials, such as acute trials, can require high concentrations of the treatments to be effective. Equally earthworm reproduction tests can take weeks to conduct. Since 1993, a protocol to test the behavioural responses of earthworms towards less favourable conditions was developed in the USA (Vanpraagh *et al.* 1993) and has now been standardised by the International Organisation for Standardization (ISO 2008). In contrast to previous trials, behavioural avoidance tests are effective at low concentrations and provide relatively rapid results (Boscolo *et al.* 1993, Jansen *et al.* 1993, Vanpraagh *et al.* 1993, Jones & Hart 1998, Hund-Rinke *et al.* 2005, ISO 2008). The ISO protocol 17512-1:2008 was modified here so that it was appropriate for testing the effects of digestate and used to measure the avoidance responses of earthworms to contaminated soils, thus assessing the risk a chemical can cause in reducing habitat function (Boscolo *et al.* 1993). A habitat function is defined by the ISO as;

"*the ability of soils/soil material to serve as habitat for micro-organisms, plants and soil-living animals and their interactions"* (McIntyre & Hunter 1975).

The importance of earthworms as an indicator for digestate suitability on organic farms is explored in greater depth in chapters two and three.

iii) Are organic farmers interested in adopting anaerobic digesters?

Although organic farmers may be interested in renewable energy technologies (Bailey *et al.* 2008) as yet, there has been little research into whether organic farmers are interested in adopting anaerobic digesters. Research needs to address the motivation of groups within the organic farming community to determine where best to target the promotion of anaerobic digesters.

The motives underlying the decision making of organic farmers have been explored in many studies (Rigby *et al.* 2001, Darnhofer *et al.* 2005, Lobley & Butler 2010). The decision to convert to organic farming has been particularly well investigated (Fairweather 1999, Rigby *et al.* 2001, Darnhofer *et al.* 2005, Lobley & Butler 2010). Exploring the motives of farmers who have converted could help in assessing their willingness to invest in other technologies like anaerobic digestion.

Organic farmers may potentially be interested in adopting anaerobic digestion technology for the benefits conferred, notwithstanding any financial incentives offered. They are also likely to be interested in reducing their pollution levels, treat their organic material, and generate sustainable energy for their farms, all of which fall within their ideals of farming sustainably.

Some organic farmers may consider anaerobic digesters unsuitable for their circumstances, even though they express support for agricultural practices that promote the same benefits as those achievable by anaerobic digester systems. This may be due to a conflict between the main type of enterprise on their farm, their organic status, or their involvement in agriculture altogether. Organic certifiers do not prohibit organic farmers from growing energy crops, although the farmer may lose subsidies on land used when growing energy crops (Natural England 2010). Opinions on this are explored in greater detail in chapter four.

Studies exist on the type of farmer who may consider adopting a scheme (Beedell & Rehman 2000, Falconer 2000, Sutherland 2010) and the type who may consider an anaerobic digester (Tranter *et al.* 2011). Currently, to this researcher's knowledge, there has been no published research examining organic farming opinions of anaerobic digesters in terms of whether these are suitable for individual types of organic farms or organic farms as a whole. This aspect needs to be addressed to establish whether it is worth promoting anaerobic digesters to this group of farmers. These issues are explored in chapter four.

iv) Energy and emission savings using anaerobic digesters

Anaerobic digesters could potentially reduce the GHG emission associated with farms by capturing GHG emissions and replacing externally sourced energy with renewable energy.

While there are studies looking into the impact an anaerobic digester could have on a conventional farm's total GHG emissions (Banks *et al.* 2011b, Kaparaju & Rintala 2011, Kimming *et al.* 2011, Masse *et al.* 2011), to the author's knowledge, there are currently no case studies assessing the impact anaerobic digesters have on organic farms (Kimming *et al.* 2011). As organic farming practices differ in the way they use energy (Pimentel *et al.* 1983, Dalgaard *et al.* 2001, Loake 2001, Deike *et al.* 2008), further research could demonstrate GHG emission savings compared with the previous case studies. It is important to establish what the potential change in an organic farm's GHG emissions may be from employing an anaerobic digester.

Within this thesis, the use of anaerobic digesters for reducing GHG emissions and energy sustainability on farms is examined in chapters four and five. The organic farmers' opinions on whether an anaerobic digester could be used as a way to reduce GHG emissions and increase energy sustainability are explored in chapter four. Two case studies are examined in chapter five, calculating the potential GHG savings that could be made on an organic farm by employing an anaerobic digester.

1.4 Aims of this thesis

The main aim of this thesis is to explore to what extent anaerobic digesters fit within the constraints and philosophy behind organic farming. To achieve this, a multidisciplinary approach is used with methods drawn from three disciplines - ecology, social science and environmental sciences. This general aim is explored through the following research questions, which make up the titles of each experimental chapter. These are then delivered through the objectives bullet pointed below each of the chapter titles below.

Chapter 2. The suitability of digestate as a fertiliser substitute

The objectives of this chapter are to:

- Determine the effects of digestate on plant growth for a weed and crop species.
- Identify the effects digestate has on weed populations.
- Assess the effect digestate application has on earthworm populations in the field.

Chapter 3. The impact from digestate application on the behaviour of earthworm species *Lumbricus terrestris and Eisenia fetida*:

The objectives of this chapter are to:

- Assess the effects on earthworm behaviour of digestate from a range of feedstock.
- Identify whether there is an earthworm species-specific preference and survival ability for slurry and digestate.
- Test the effects the age and concentration of digestate have on earthworm behaviours.
- Discuss the suitability of species for experimental analysis.
- Identify potential long-term effects from digestate application.

Chapter 4. A study of organic farmers' opinions about on-farm anaerobic digesters

The objectives of this chapter are to:

- Investigate whether organic farmers consider anaerobic digesters to be an attractive enterprise for organic farming
- Identify what the barriers are towards adopting an anaerobic digester and whether these differ for conventional farmers.
- Create a profile of the type of farmer that is more likely, and less likely, to consider investing in an anaerobic digester.
- Identify areas where improvements should be made to improve the anaerobic digestion market within organic farming

Chapter 5. An assessment on the impact an anaerobic digester can have on a farm's carbon footprint

The objectives of this chapter are to:

- Assess the impact of an anaerobic digester system on a farm's total carbon equivalent emissions.
- Identify how far anaerobic digesters can make farms energy self-sufficient.
- Highlight the limitations anaerobic digester plants have on the total emissions created by agricultural practices.

Chapter 6. General Discussion: To what extent can anaerobic digesters be used on organic farms? How does the use of anaerobic digesters conflict with or compliment the IFOAM's definition of organic farming.

Chapter 2:

The suitability of digestate as a fertiliser substitute

2.1 Introduction

The International Federation of Organic Agriculture Movements (IFOAM) emphasise the importance of the "*health of the soils*" whilst discouraging "*inputs with adverse effects*" (IFOAM 2008). They believe they can do this by avoiding the use of synthetic fertilisers (see section 1.3.1 for more details). As a substitute, they use other agricultural methods to replace nutrients lost. These include crop rotation, growing green manures, and the recycling of organic material such as manures (Lampkin *et al.* 2008). Although less environmentally harmful in terms of greenhouse gas (GHG) emissions, than the production of synthetic fertilisers (Deike *et al.* 2008), the storage and use of animal manure is a major source of methane emissions from agriculture (Dench *et al.* 2004). Using an anaerobic digester is one method of reducing emissions from stored manures whilst improving soil fertility by using the residual material, the digestate, as a fertiliser (Amon *et al.* 2006, Yiridoe *et al.* 2009).

Due to the restrictions organic certifiers place on what fertilisers can be used, (Soil Association 2009b), to verify that digestate complies with organic standards, a thorough assessment of the effects digestate may have on the environment is required. If digestate application causes harmful environmental effects, in particular to the soil biota, crop production may be negatively affected and the digestate would be deemed unsuitable for organic use.

The breakdown processes involved in anaerobic digestion can alter the original feedstock by reducing the organic matter (OM), increasing the pH and increasing the ammoniacal content (Wulf *et al.* 2002a, Clemens *et al.* 2006, Ernst *et al.* 2008b). These changes mean that digestate provides nitrogen to plants in a more readily available form, more similar to that present in inorganic fertilisers (Moeller & Stinner 2009). This does not necessarily mean digestate will produce as high a yield as inorganically fed crops (Bermejo *et al.* 2010). The total carbon content of digestate is also reduced which can lead to a more balanced carbon to nitrogen ratio (Moller 2009). Nitrogen nutrients in digestate are available in a more immediate, inorganic form to plants, and less are in an organic form, which are accessible to soil microbes. Together this and the reduction of OM levels in digestate may reduce the amount of available nutrients for soil biota to feed off, therefore reducing their numbers (Ernst *et al.* 2008b) (see section 1.3.2.ii for more details). Such detrimental effects may be crucial to the ecological functions within the soil as many of these species play an important role in helping to deliver ecosystem services (Dench *et al.* 2004).

It is the feeding interactions between soil species, the soil and organic fertilisers, which enables manure based fertilisers to be as successful in crop production as chemical fertilisers (Edmeades 2003). In particular, earthworms are a key species which facilitate soil interactions such as the breakdown of organic material. They are also responsible for turning and incorporating organic matter into the soil, increasing water filtration, influencing nutrient dynamics as well as many additional functions (Edwards & Lofty 1972, Syers & Springett 1984, Dominguez *et al.* 2004). Because of their many beneficial functions, they are considered a major ecosystem engineer and essential for maintaining soil fertility (Sheehan *et al.* 2007). A change in the regular fertiliser used such as from slurry to digestate, could result in a disruption to earthworms' established behaviours and population numbers. A reduction in numbers, for example, could result in lower fertility and low quality soil (Mader *et al.* 2002).

As well as restrictions on chemical fertilisers, pest and weed control options for organic farmers are also highly regulated, and many chemical options are prohibited (Lampkin *et al.* 2008, Soil Association 2009b). Weed management is therefore a problem for organic farmers and requires more time-consuming husbandry methods when compared to those available to conventional farmers (Blake 1990, Lampkin *et al.* 2008). Weed seeds passing through the cow's gut into the manures can be reintroduced onto the field through the application of manures. To reduce this, treatments such as composting are used, which can kill many weed seeds and pathogens (Blake 1990, Wiese *et al.* 1998, Larney & Blackshaw 2003). Weed growth can also be reduced by the physical presence of the OM on the surface and/ or the phyto-toxic compounds generated by microbes in the composting process. Treating manures using anaerobic digestion has also been found to reduce plant pathogens and weed seed survival, (Engeli *et al.* 1993, Katovich & Becker 2005, Yiridoe *et al.* 2009) and the shadowing presence of digestate on the soil surface has too shown to decrease the success of weed seed germination (Ozores-Hampton 1998). As the digestion process reduces the amount of OM in the digestate, this shadowing effect is likely to be lower than that achieved by manures. It is therefore important to compare whether the reduction in OM in digestate has a reduced effect on weed growth at agricultural concentrations.

The aim of this chapter is to assess the suitability of digestate as an organic fertiliser in regard to three potential agricultural factors;

1) To determine what effects digestate has on the short term biomass production for both crops and weeds. Here, Italian Ryegrass (*Lolium multiflorum*) is used as an example of a crop, and Creeping Thistle (*Cirsium arvense*) is used as a common agricultural weed (Pattey *et al.* 2005).

2) To identify whether digestate can act as a method of either weed transmission or suppression. Here, Creeping Thistle is used as an example due to its persistence in agricultural fields (Pattey *et al.* 2005).

3) To assess the effect of digestate on earthworms' populations through field trials, and whether these effects are different to that seen after slurry application. The results of this will then be used to aid the creation of the aims for chapter 3.

2.2 Methods

Glasshouse and field experimental methods were used to assess digestate as a fertiliser. The results from the laboratory methods were used to validate the findings from the field experiments. The results from this chapter can also be used to support the findings reported in chapter three.

Three fertiliser treatments were used,

1) organic slurry

2) digestate produced using slurry from the same source as treatment 1

3) no treatment (control)

The slurry was collected from an open topped slurry tank, and the digestate was produced in a mesophilic anaerobic digester. Both treatments were sourced from Lodge Farm, Wrexham, UK (SJ 338354). Slurry and digestate for glasshouse studies were stored at 4ºC to minimise changes to chemical composition. Due to the large volume, the treatments for the field trials were stored at ambient temperature at the field site. Two batches of each treatment were collected, the first in February 2010, and the second in July 2010. This ensured the material was fresh at the start of each trial and not affected by prolonged storage.

Total Kjeldahl Nitrogen (TKN) values were calculated for both slurry and digestate for both samples using the Kjeldahl method (Webb *et al.* 2004). The nitrogen value for digestate was 2460 mg l^{-1} in the first sample and 2011 mg l^{-1} in the second. The raw slurry was 1937 mg l^{-1} in the first sample and 1798 mg l^{-1} in the second. The percentage dry weight for the slurry was on average 4.0%, and for digestate, was 1.3%. These values were used to calculate the loading rates for the glasshouse and field experiments to ensure the nitrogen content for each treatment was kept the same.

2.2.1 Glasshouse methods for weed and crop growth

The glasshouse trials were conducted at 20ºC ± 2ºC on a 12:12 light to dark regime, with water added three times a week to the top of plant pots (plastic, 10cm in diameter). Loam topsoil purchased from B&Q (Southampton store- head office; Torrance House, Erskine, Renfrewshire, PA8 6AT, UK) was autoclaved and used as the main growing medium.

i) Potential contamination from treatments

Digestate and slurry were tested to ensure they were not vectors of weed seeds for the laboratory and field trials. This was done by add 20ml of digestate to 20 pots of autoclaved loam topsoil, 20ml of slurry to 20 pots of autoclaved loam topsoil, 20g of soil from the field site to 20 pots of autoclaved loam topsoil, and 20ml of water to 20 pots of autoclaved loam topsoil. After 30 days the frequency of seedling emergence was recorded for each pot.

ii) Seedling growth

Organic Italian Ryegrass (*L. multiflorum*) (purchased from Cotswolds Seeds Ltd, Gloucestershire, UK), and Creeping Thistle (*C. arvense*) (seeds harvested from plants near the field plot site) were scattered onto autoclaved soil at 60 mg $cm^{2\ -1}$. A treatment of either the slurry or digestate was added at a concentration of 63 kg N ha^{-1}. This concentration was calculated from using 250kg N ha^{-1} yr^{-1} and divided into four spreads, a figure suggested by farmers through the regular emptying of their slurry stores through the year. For the control, the equivalent volume of water to that of the digestate water content was added to the soil. The total count of thistle seedlings that emerged after 30 days was recorded. The surface biomass for both thistle and ryegrass was collected and weighed using an OHAUS Analytical Plus AP250D top-pan balance to an accuracy of ± 0.001 g. Samples were then dried at 70ºC until no further weight loss occurred and final mass recorded to ± 0.001 g.

iii) Glasshouse statistical analysis

The presence or absence of seedlings was used to determine whether either treatment was a vector for weeds. The number of thistle that emerged, the wet and the dry mass for both grass and thistle seedlings were analysed using ANOVA for between treatments using Minitab ® Statistical Software v16.1.0. (Minitab Inc., State College, PA., USA).

2.2.2 Field plot methods

Field trials were conducted between April 2010 and November 2010 at Chilworth Science Park, Southampton, UK (SU 440118). The plot site had been free from agrochemicals for at least two years prior to the start of the trial. Nine plots 9 m^2 with 2 m margins between plots were cleared by weeding and ploughing. The site was then treated as a newly sown organic grassland (Lampkin *et al.* 2008). Organic Italian Ryegrass as described above was scattered at a concentration of 5.5 g $m^{2\ -1}$ (Dates: 15/04/10 and 15/07/10). No artificial irrigation was used during the trials.

Each of the three treatment types were assigned to plots in a Latin Square design (Fowler *et al.* 1998), allowing three replicates for each treatment (Figure 2.1). Treatment was spread at a volume of 3.4 l $m^{2\ -1}$ for digestate and 3.9 l $m^{2\ -1}$ for slurry. This was to achieve a concentration of around 70 kg N ha^{-1} to each plot (Dates: 22/04/10 and 30/09/10) and represented the spread rate of previous studies (Cotton & Curry 1980a). Back calculations showed each plot received around 71.9 kg N ha^{-1}. Treatments were spread using a watering can to represent hose pipe trail application. During the April application, the soil was raked over to ensure an even cover. By the September spread, vegetation had established, making the rake over impossible.

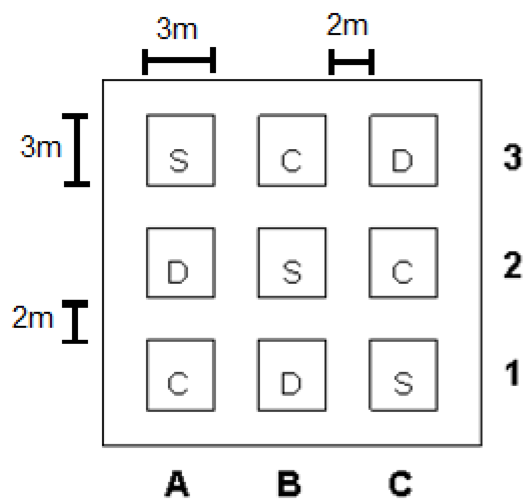


Figure 2.1. Latin square design of treatment arrangement. Plots are referred to as; rows (along the X axis: for example row one refers to plots = A1, B1, C1), and columns (along the y axis, for example, column A refers to plots = A1, A2, A3). Treatments are S = slurry, D = digestate, C = control (no treatment).

i) ***Plant germination in field plots***

Plots were monitored for wild plant growth on five occasions between March and June 2010 (Dates: 15/04/10, 10/05/10, 24/05/10, 31/05/10 and 07/06/10). Total count and percentage cover for bramble (*Rubus fruticosus)* and thistle (*Cirsium* spp.) emergence were recorded. Total percentage cover of grass (*Poaceae*), and 'all other plants' growing in the plots was recorded. The sampling orders of the plots were randomised, and repeated, with the average of the two figures used for analysis. Cover estimation and counts were performed by the same researcher to eliminate individual effect.

ii) Earthworm sampling from field plots

Earthworm samples were taken three times between April and June 2010 (Dates: 15/04/10, 28/04/10 and 02/06/10), and three between September and November 2010 (Dates: 23/09/10, 08/10/10 and 11/11/10). Spring and autumn spreading was chosen to represent when farmers are likely to spread to empty their stores- just after the winter spreading restrictions, and just before the spreading restrictions as recommended by the (DEFRA, 2009d). These months are also when earthworms are most active (Edwards & Lofty, 1972). Samples for both seasons took place one week prior, one week after, and six weeks after slurry/digestate treatment. An area of soil 160 cm^2 to a depth of 15 cm from each plot was hand sorted for individuals. Sorting time was standardised to 45 minutes per soil sample. This volume of soil has been suggested to be adequate to estimate populations of medium-sized earthworm species (Edwards & Lofty 1972, Booth *et al.* 2001). Earthworms located 15 cm below the surface were retrieved by pouring into the hole three litres of mustard solution (purchased from Spiceworld, Somerset, UK) diluted with water to a concentration of 15 mg l^{-l} (Gunn 1992, Chan & Munro 2001, Pelosi *et al.* 2009). Earthworms that emerged within 15 minutes were added to the collection soil bag to be hand sorted. Sorted earthworms were stored on wet paper towels at 10ºC for 24 hours to allow their guts to empty. They were then rinsed, dried and weighed using an OHAUS Analytical Plus AP250D balance to an accuracy of ± 0.001g. Due to earthworms escaping from the first sample during the gut emptying period, mass analysis was only conducted on the data from the second set of trials.

Environment variables were measured on each day the earthworms were sampled. Day and soil temperature was recorded using an UEi PDT550 thermometer. Soil moisture was taken using a Delta- T HH2 moisture meter with Theta Probe, type ML2x and measured percentage water content. An averaged value over five moisture samples taken from random locations within each plot was used for analysis.

iii) Field plot statistical analysis

Emergence data for the thistle count was analysed using a General Linear Model (GLM) for repeated measures. Grass percentage cover and “other plant: cover data were normalised using square root transformation and analysed using a GLM for repeat measures in SPSS in SPSS v18 (SPSS, IMB corporation, NY,. USA). SPSS was used rather than Minitab as the latter is unable to perform GLM and repeat measures on data. Thistle cover data were log+1 transformed and analysed using ANOVA in Minitab ® Statistical Software v16.1.0 (Minitab Inc., State College, PA., USA). Data for bramble count could not be normalised through transformation, and so were analysed using a Kruskal-Wallis test in Minitab.

Earthworm frequency data was not normally distributed and could not be normalised through transformation, so were analysed with a Kruskal-Wallis test to compare between treatment types and sampling dates. Earthworm frequency data were analysed with a T-test for slurry and digestate treatments against values for the control plots. All statistics on earthworms were analysed using Minitab (v.16.1.0). Due to the low data count for each mass category, no statistics could be performed on earthworm mass before and after application and only observational comments are made on these results.

Soil moisture data were log transformed and analysed using an ANOVA between; treatments (slurry, digestate, control), row (A, B, C), column (1, 2, 3) and row column interactions, and sample (1 - 6) (nested in trial (1 - 2)). Soil temperature could not be transformed, and so were analysed using Kruskal-Wallis test between treatments (S, D, C), row (A, B, C), column (1, 2, 3) and sample (1 - 6).

2.3 Results

2.3.1 Glasshouse trials

i) Contamination from treatments

No seedling emergence was recorded from the pots containing either treatment, suggesting that slurry/ digestate are not vectors for potential plant contamination. This meant that the slurry and digestate were both suitable for experimental use and all the plants that emerged during the glasshouse trials were introduced by the researchers, and the plants that emerged on the field plots originated from the seedbed already existing in the plots. Pots containing seedbed soil contained seeds, with an average of 3.7 (SE ± 0.42) seedlings germinating per pot. The control autoclaved soil pots had an average of 0.05 seedlings per pot.

ii) Seedling growth in treatments

Average thistle seedling wet mass ($F_{2,27}$ = 2.10, P = 0.14) and dry mass ($F_{2,27}$ = 1.27, P = 0.30) did not differ between the three fertilising treatments (Figure 2.2). There were no significant differences in the number of seedlings emerging per pot for each treatment ($F_{2,27}$ = 1.99, P = 0.16), no difference in the average wet mass per plant ($F_{2,27}$ = 0.84, P = 0.44) and no difference in the average dry mass per pot ($F_{2,27}$ = 0.07, P =0.94).

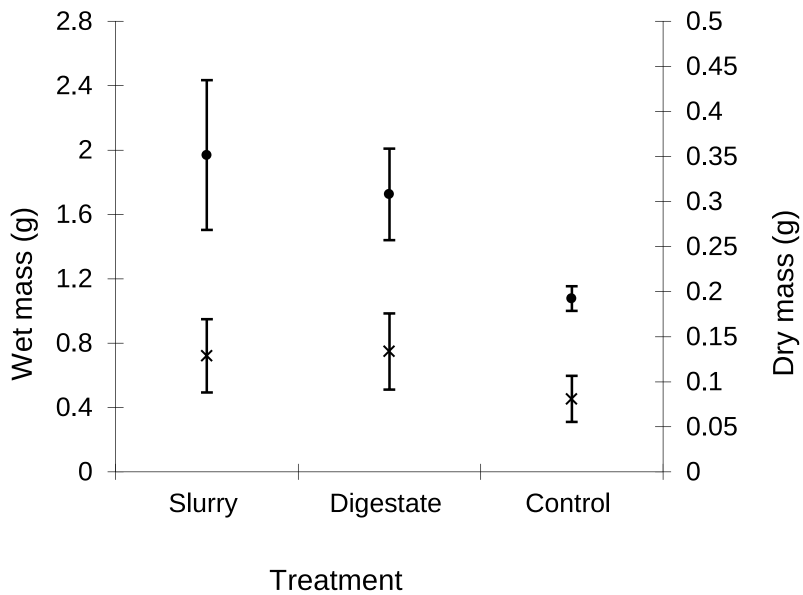


Figure 2.2. Wet (●) and dry (X) mass per pot of thistle seedlings grown in three fertilising treatments. Bars represent ±SE. No significant differences in wet mass data and the dry mass data were found between any of the treatments.

Ryegrass seedlings in control conditions had a lower wet mass, and seedlings grown in digestate had a higher wet mass, compared with seedlings grown in slurry ($F_{2,27} = 17.92$, $P < 0.001$) (Figure 2.3). Dry mass values for ryegrass were also higher in seedlings grown in digestate, compared with those receiving slurry or no treatment. ($F_{2,27} = 12.54$, $P < 0.001$).

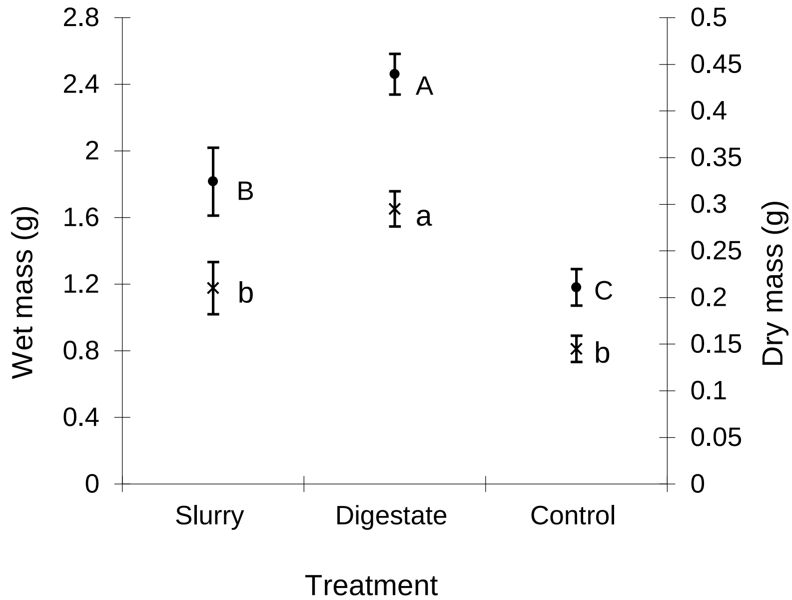


Figure 2.3. Wet (●) and dry (X) mass of ryegrass seedlings grown in three fertilising treatments. Bars represent ±SE. Letters denote significant difference between treatments. Uppercase letters represent wet mass significance, and lower case represent dry mass significance between the three fertilising methods.

2.3.2 Field plot trials

i) Environment analysis

Soil moisture differed between the three time samples taken ($F_{4,48}$ = 29.80, P <0.001) with moisture increasing with time for each sample (nested in trial) ($F_{2,51}$ = 33.66, P <0.001). There was no effect of plot row ($F_{2,45}$,= 0.69, P = 0.51) and column ($F_{2,45}$ = 0.83, P = 0.44) or row column interactions ($F_{4,45}$ = 0.15, P = 0.96), or treatment type to the plot ($F_{2,51}$ = 0.23, P = 0.79) on the variation of soil moisture between plots (Figure 2.4).

Soil temperature differed significantly between sample times (H_4 = 48.84, P <0.001) with temperature increasing during the first trial period (samples 1 - 3) ($F_{1,25}$ = 337.49, P <0.001), and decreasing during the second trial period (samples 4 - 6) ($F_{1,25}$ = 217.24, P <0.001). There was no effect from row (H_2 = 0.01, P = 0.99) or column (H_2 = 0.01, P = 0.99) or treatment type to the plots (H_2 = 0.19, P = 0.91) on the variation of soil temperatures between plots.

As both soil temperature and soil moisture (Figure 2.4) depended only on the sample number (1 - 6) and not between the effects of treatment, or bias between plot locations (row or column location), environmental factors were all similar between plots, so these variables were not incorporated into further analysis.

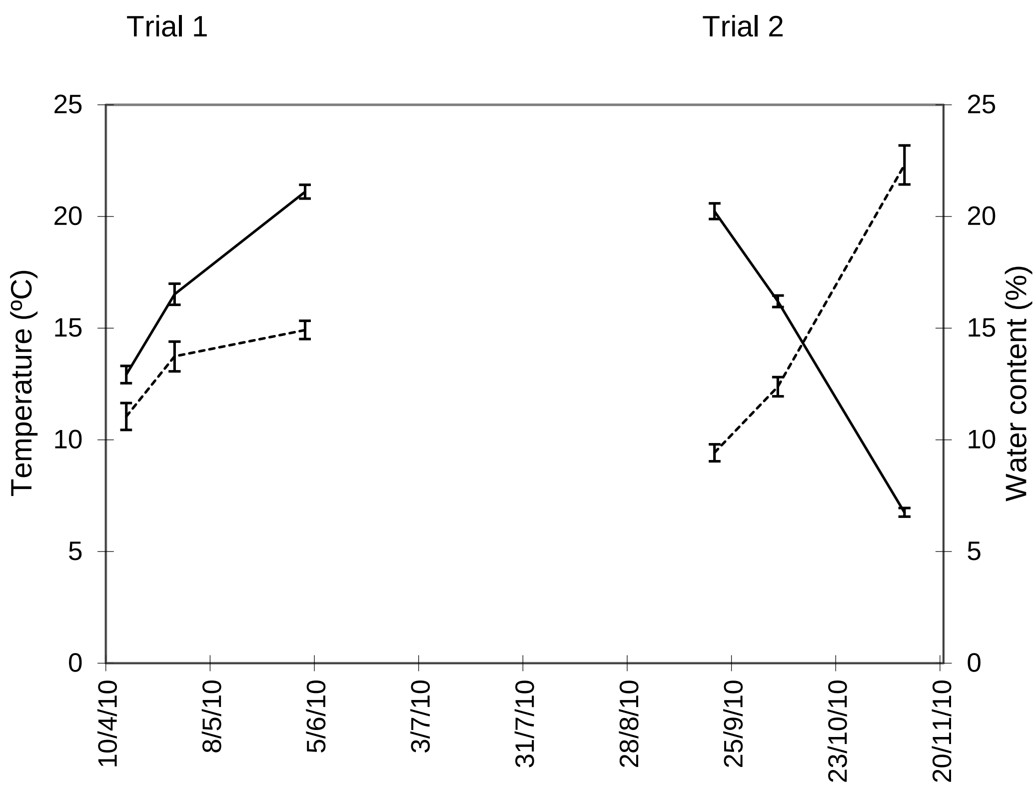


Figure 2.4. Variation in soil temperature (bold line) and soil moisture (dashed line) over the two trials, for six time samples. Bars represent ± SE variation between all nine plots.

ii) Plant germination from field plots

There was an increase in thistle emergence over all plots with time (Figure 2.5a). Reduced emergence was seen in plots treated with digestate and slurry compared with no treatment ($F_{.56,19.66}$ = 4.66, P <0.01.). No significant difference was found between plots treated with digestate (T_3 = -0.36, P = 0.74) or treated with slurry (T_3 = -3.04, P = 0.06) compared with the control plots (Figure 2.5b).

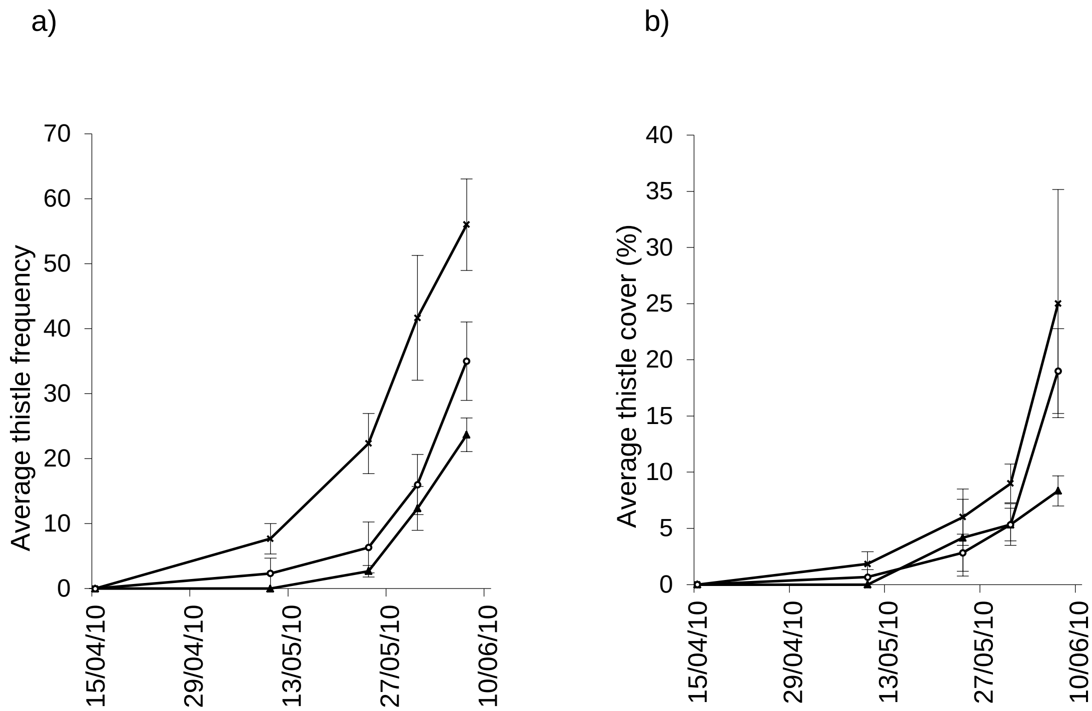


Figure 2.5. Average thistle a) frequency and b) percentage cover in field plots (N = 3) for three fertilising treatments; Control (x) slurry (▲) and digestate (o). Bars represent ±SE.

Location of the plot had a significant effect on the number of brambles emerging along the row (higher in row C ($H_2 = 22.67$, $P <0.001$)) but not for the column location ($H_2 = 1.22$ $P = 0.55$). Number of emerging brambles did not increase with time ($H_2 = 1.44$, $P = 0.70$), and levelled off after sample three (Figure 2.6a). The number of brambles significantly differed between treatments ($H_{2,} = 6.27$, $P <0.05$) with the most on the control plots (mean per sample = 10.42 ± 2.92), followed by digestate treated plots (mean per sample = 6.83 ± 2.68) and the least on the slurry treated plots (mean per sample = 5.42 ± 2.48).

The percentage of bramble cover was influenced by the treatment type, ($F_2 = 6.77$, $P<0.01$) with more cover on control plots (mean per sample = 5.13 ± 1.12) followed by digestate (mean per sample = 3.13 ± 1.26) and the least on slurry treated plots (mean per sample = 1.792 ± 0.74) (Figure 2.6b).

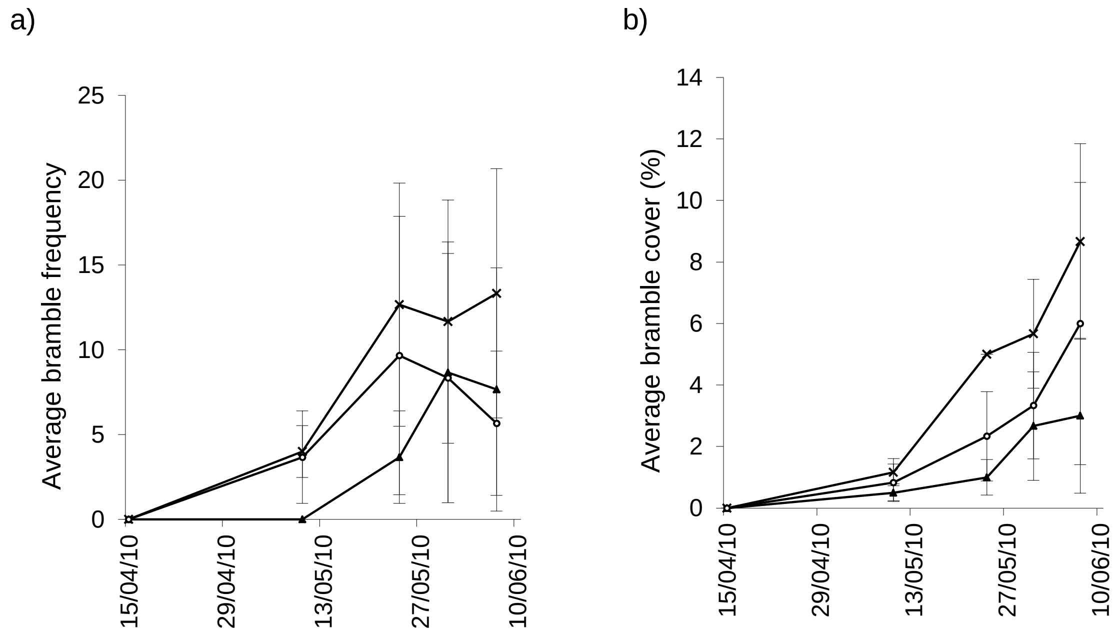


Figure 2.6. Average bramble a) frequency and b) percentage cover in field plots (N=3) for three fertilising treatments; Control (x) slurry (▲) and digestate (o). Bars represent ± SE.

iii) Earthworm emergence from field plots

Treatment application had an effect on earthworm frequency ($F_{2,6}$ = 9.88, P <0.05) between one week before and one week after treatment application for plots treated with slurry and the control plots for both trials (Tukey, P <0.05). By six weeks after application, treatment no longer had an effect on earthworm frequency ($F_{2,6}$ = 3.73, P = 0.09). The application of slurry for both trials increased earthworm frequency (Figure 2.7). The plots treated with digestate and the control plots had an average decrease in earthworm frequency collected during the first trial (Spring sampling) and an increase in earthworm frequency collected during the second trial (Autumn sampling).

While digestate treated plots saw an increase in average earthworm frequency similar to that seen in slurry treated plots, they were not significantly different from the earthworm numbers found in the control plots principally due to the large variation seen between repeat plots (T_4 = 1.78, P = 0.15).

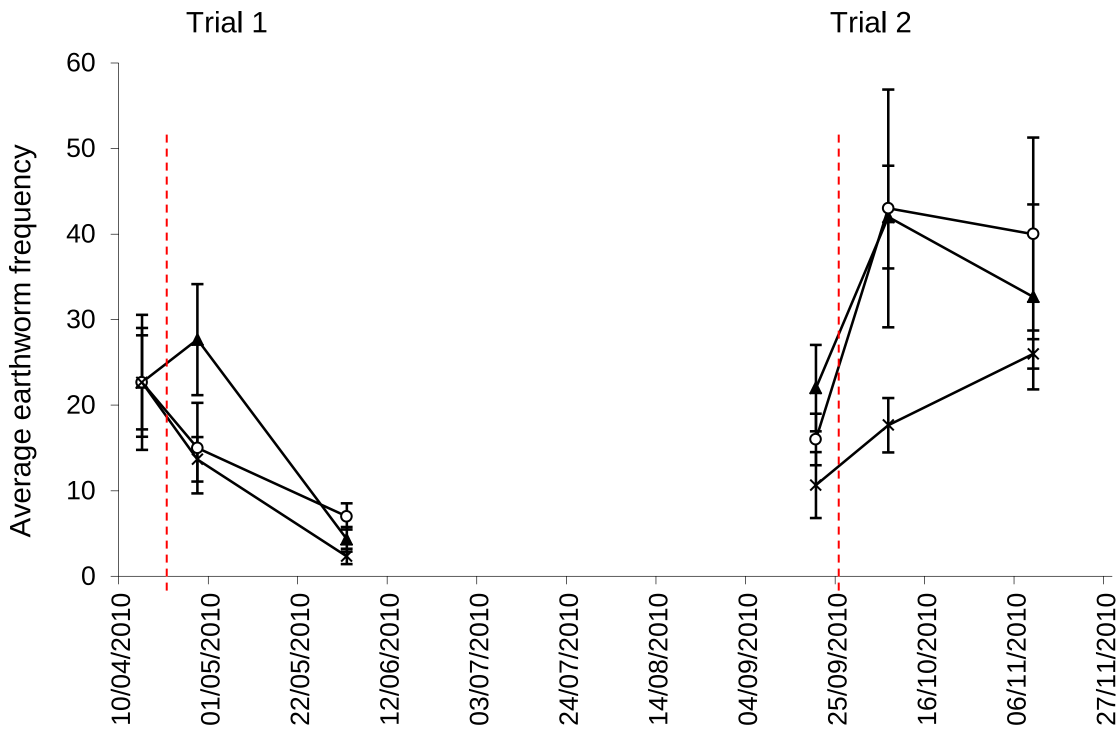


Figure 2.7. Average frequency of earthworms for three different fertilising treatments; Control (x) slurry (▲) and digestate (o). Bars represent ±SE Dashed line represents application of treatment.

During trial two, individual earthworm mass increased between one week before and one week after treatment was applied (H_2 = 8.28, P <0.05) with earthworms in slurry treated plots on average larger than earthworms located in digestate or control plots (Figure 2.8). Earthworms in plots treated with slurry were also significantly larger one week after treatment, compared with one week before (T_{188} = -2.18, P <0.05). There were no significant differences in earthworm mass between the treatments one week before application (H_2 = 0.28, P = 0.87), nor at six weeks after application (H_2 = 1.28, P = 0.53) (Figure 2.8).

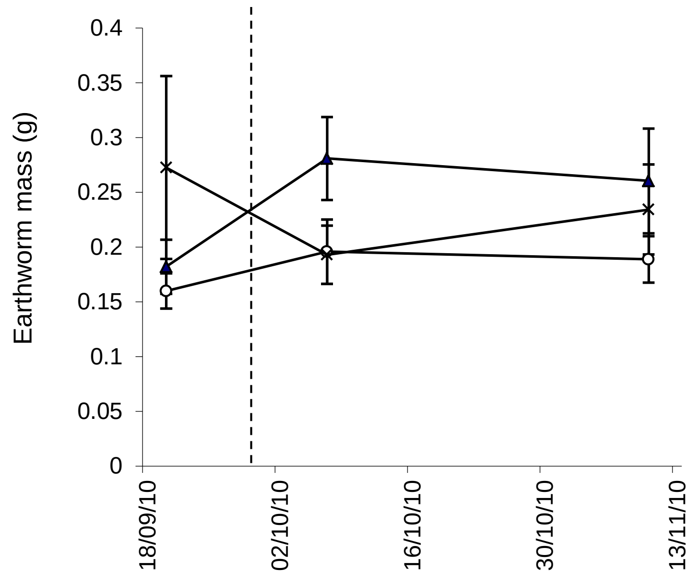


Figure 2.8. Average earthworm mass for three fertilising treatments during trial 2 only; Control (x) slurry (▲) and digestate (o) at one week prior, one week after and six weeks after application. Bars represent ± SE. Dashed line represents date treatment was applied.

There appeared to be more large individuals found in the plots after being treated with slurry and digestate, than before treatment was applied. As the frequency of earthworms for each size category was too small to conduct robust statistical analysis, only a trend can be identified here (Figure 2.9).

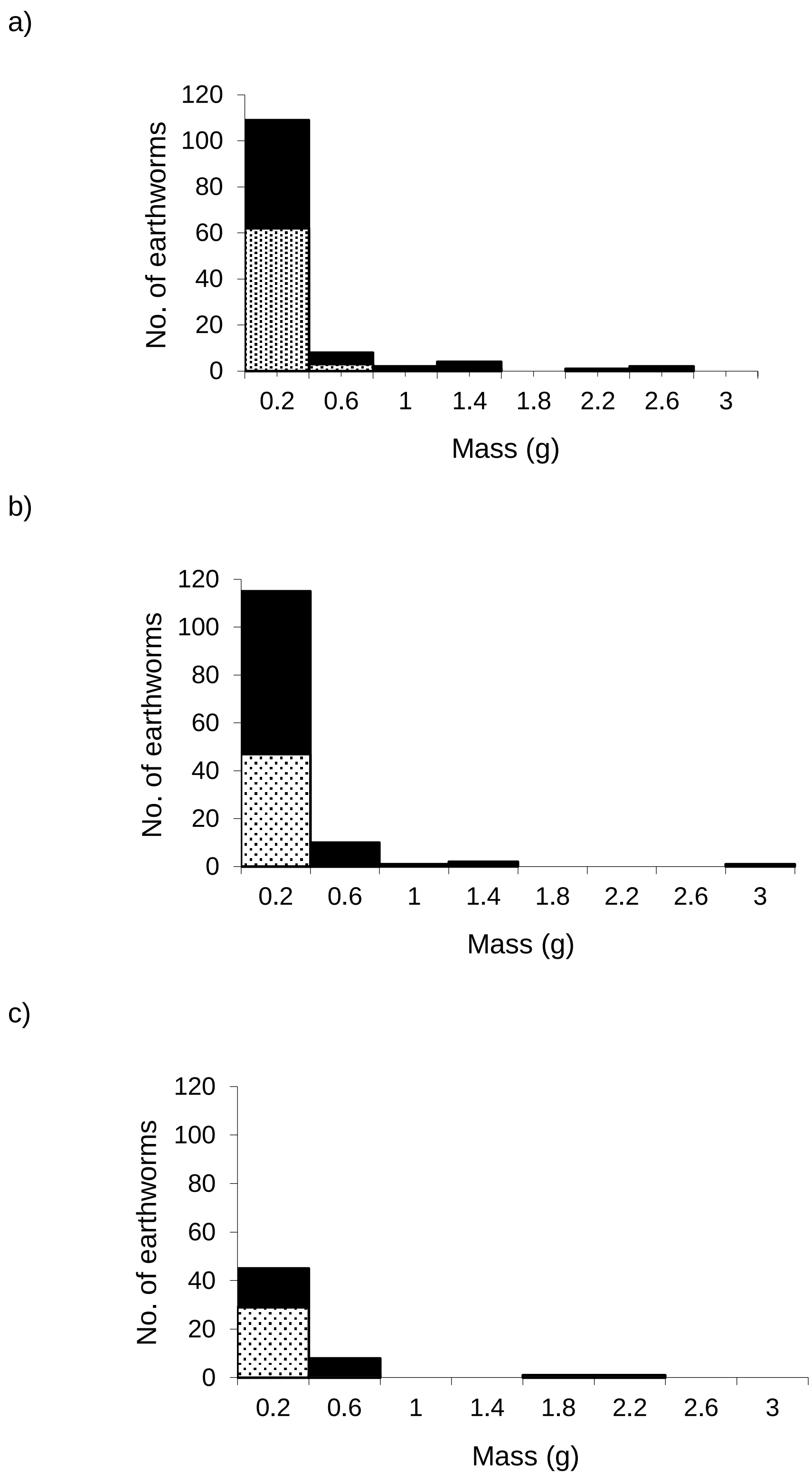


Figure 2.9. Size distribution of earthworms from each field plots one week before (spotted bars) and one week after (block coloured bars) application of treatment a) slurry, b) digestate and c) control.

2.4 Discussion

Chemicals added to soils can disrupt established nutrient and ecological cycles effecting crop quality and yield. Here both digestate and slurry had positive effects on weed suppression and crop growth, while the effect on earthworm populations requires more research to gain a better clarification.

2.4.1 Effects of treatment on weeds

i) Thistles

The suppressing effects of the slurry and digestate application may be linked with the additional volatile organic compounds (VOC) found in both treatments. VOCs in immature compost can suppress weed emergence and growth (Ozores-Hampton 1998, Ozores-Hampton *et al.* 2002). As untreated feedstock usually contains more VOCs than its digestate residual, this may explain why slurry was the better weed suppressor. Shading weed seedlings also reduces their ability to grow (Fan & Gerowitt 2002). Direct application of the treatments creates a thin layer of organic matter over the soil surface, which is visible even one week post-application. It was also observed that the slurry treated plots retained a covering for a longer period than the digestate treated plots (personal observation), the slurry having a higher OM content than the digestate created a thicker layer over the soil surface. This may further explain why the plots treated with slurry had a lower weed emergence than the digestate ones.

The treatments may have had indirect effects on the weeds by allowing other plants to grow rapidly, due to the additional nitrogen, which may then have competed with the thistles for resources such as light. This effect may have negative consequences if the crop grows slower than weeds, for example, as seen with wheat (Blackshaw *et al.* 2005). In addition, high levels of nitrogen can be directly toxic (McIntyre & Hunter 1975) for instance digestate treatment increases ammonia concentrations from the original feedstock (See review by Britto & Kronzucker 2002 and chapter 3 for digestate and slurry analysis). However in this study, levels applied were in line with common practice, and are not considered high enough to cause toxic effects.

Although fewer thistles germinated in the treated plots, by the end of the trial, there was no different in cover from thistles between treatment types. This may suggest that weeds that were able to germinate, may have used the additional nitrogen applied to grow more rapidly and occupy large individual percentage covers. This may then have led to the cover differences not being significantly different. Treatment application may only have had a limited effect on weed suppression before weeds become competitive for space and light resources.

No effect from treatment was seen on thistle emergence or mass production within the glasshouse experiments. This may have been linked to the watering regime for the pots. Water was added to the surface of the pots- washing off the potential shading effects created by treatment application. No other plants were grown within the pots, and so there was no competition for light resources. It also appears the additional nitrogen added through the application of the treatments was not used to facilitate thistle growth as there was no difference between the dry or wet mass of the three treatments.

ii) Brambles

High densities of brambles were located on one side of the field site, creating a bias in the plot location. Although many of the underground rhizomes were dug up during the initial site preparation, it is unlikely all were removed. This would have enabled plots near to bramble patches to be re-colonised more quickly than others. If unmanaged, brambles can become a weed and can cause smothering other plants and suppressing ground fauna (Radosevich *et al.* 1997). Within this study, treatment application appears to reduce the number of brambles that emerged, with slurry reducing emergence over control plots. Although these results were statistically significant, and a Latin square design was used to minimise location effects, the high influence of the location of the individual plots, and low number of repeats, means that the results should be treated with caution. Further work with a more controlled environment, more repeats, or after a more thorough clearance of the plots is needed to provide more reliable results. This could be performed using mesocosm experiments to help support the findings of this experiment and help reduce environmental variation.

2.4.2 The effects of treatments on grass

Digestate can be used as a fertiliser for grass as here; both the wet and dry mass of Italian ryegrass was greater either than the mass of the grass treated with slurry or with no treatment. However addition of nitrogen may be detrimental to other plant species. Organic farmers often rely on clover to help fix nitrogen back into the soil, as well as increase the quality of their silage for animal feed (Lampkin *et al.* 2008) and is often incorporated into rotations or pastures (Blake 1990). Clovers show reduced nitrogen fixation, and overall yields when fertilisers are added. This occurs both with mineral (Crush *et al.* 1982, Curll *et al.* 1985) and natural sources of nitrogen, such as in manure (Curll *et al.* 1985). Farmers have limited storage space for organic fertilisers and so need to dispose of them onto land. For dairy farms, this is likely to be spread onto grasslands containing clover. If the form of nitrogen found within the digestate affects nitrogen fixation in clover, its use may have to be restricted or carefully monitored on clover rich fields. Possibly separating the digestate solid and liquid faction and minimising the spread of the high nitrogen liquids over clover grasslands may be required. Clover count was not sampled within these trials, but would be an important crop to consider for future plot trials.

Due to the nature of running plot trials and laboratory trials, it was not possible to equalise the nutrients within the soils between the two experiments. This may have led to a difference in responses and therefore the results must be treated with caution when they are compared to one another. It was also assumed that the nutrients within each of the plots were similar to one another- and that differences were accounted for through the Latin square design.

2.4.3 The effects of treatments on earthworms

Seasonal fluctuations are the likely reason for the overall decrease in earthworm frequency during trial one for all treatments after six weeks (Edwards & Lofty 1972). There may have also been an overall drop in earthworm numbers due to the high level of disturbance caused by the plot preparation (Whalen *et al.* 1998, Didden 2001, Curry *et al.* 2002, Pfiffner & Luka 2007). An increase in earthworm frequency and mass was seen in the slurry treated plots one week after application. While this could potentially be linked with the increase in OM availability to earthworms as a food source (Edwards & Lofty 1982, Pfiffner & Luka 2007), the OM could also have provided surface cover over the bare soil. The digestate application also increased the available OM, although to a lesser extent than on the slurry treated plots (slurry had a 2.3X higher %DW compared with digestate from the same feedstock type). Although digestate treated plots had more OM than the control plots, earthworm frequency in the two plot types were not significantly different.

Grass and other plant cover had established before the start of trial 2, reducing the negative impact exposure can have on earthworm behaviour. During this trial, the plots treated with digestate showed a similar increase in earthworm frequency as that seen in the slurry treated plots. Although numbers of earthworms were similar between slurry and digestate plots, no difference was found between the earthworm frequency found in control plots, and those found in the digestate treated plots. There was also a large variation in the number of earthworms found within treatments, which affected the significance of the statistical tests. More repeats would therefore be beneficial to enable clear conclusions to be drawn.

The results of the field plot experiments are highly dependent on earthworm distribution within the sampled area being representative of the whole area. Small scale variation, without explanatory environmental variables, has been seen in earthworm numbers, mass and between and within species distribution, over short distances of up to 10 meters (Rossi *et al.* 1997, Rossi 2003a, Rossi 2003b, Frund *et al.* 2004). This suggests care should be taken when implying large scale behaviours from small scale plots and that laboratory experiments may be more appropriate to investigate the effects of digestate and slurry on earthworm behaviours and survival rates (See chapter three for more details). For example, better control by standardising the soil quality and the watering and light regimes between plots would have strengthened the final result. Alternatively, incorporating research based on an intermediate level of control between the field trials and the laboratory trials may support inferences between the data sets. Here, natural field environments can be used as tests, provided features such as watering regime, species movements, and soil qualities are controlled for. Such mesocosm experiments studies have been used to validate the results from both field and laboratory experiments in behaviours and population dynamics of earthworms (Svendsen & Weeks 1997a, Svendsen & Weeks 1997b, Mathieu *et al.* 2010, Laossi *et al.* 2011).

A change in earthworm species composition between plots may be evident due to the earthworm mass and frequency data collected. Within the slurry plots more and larger earthworms were found. This may mean slurry attracts earthworms to the plot. Although official species identification was not carried out on all individuals the larger species were identified as *L. terrestris.* Due to the large margin between plots, it is unlikely the earthworms would have been repelled from neighbouring plots into the slurry treated plots. Digestate treated plots also recorded an increase in earthworm frequency, but saw a decrease in individual average mass. This may suggest the earthworms found in the plots are on average smaller, or alternatively, the plots may be attracting other individuals or species that are attracted to digestate. As the average mass was lower, the individuals migrating into the plot may either be smaller individuals, for example an increase in the number of juveniles, as seen in other studies during the autumn time sampling (Edwards & Lofty 1980), or a high immigration and aggregation of small species individuals (Rossi & Lavelle 1998). Due to the low numbers of total earthworms found, analysis was not suitable to detect a difference in earthworm mass distribution.

Changes in earthworm species composition may suggest a species preference to the treatments. This could affect earthworm communities in agricultural fields, and affect the farmer’s soil fertility. The effect of digestate and slurry on different species is explored in chapter three and emphasises the importance of species preference to treatment types.

2.5 Conclusions

A number of conclusions can be drawn from this chapter regarding the usefulness of digestate as an alternative organic fertiliser. These are;

- Digestate can be used as a fertiliser for important crops such as grass as it improves biomass production- although further work is required to clarify the effects on land that are clover rich.

- Compared to adding no treatment, digestate had the same ability to suppress thistles and brambles as slurry. It could therefore help organic farmers with their weed management.

- Digestate does not negatively affect earthworm populations, although there may be a species dependent response to treatment type. This effect may have a knock-on effect to existing communities.

The results of this chapter can offer some important management consideration when using digestate as a substitute for slurry, including application timing and types of crops to fertilise. To make the findings of this chapter more relevant to an agronomic situation, larger field trials are needed.

Data from this chapter has been published (please see appendix 8).

Chapter 3:

The impact from digestate application on the behaviour of earthworm species *Lumbricus terrestris and Eisenia fetida*

3.1 Introduction

On-farm anaerobic digesters can be fed on organic material sourced from the farm. This includes manure, slurry and residual crops. Digestate, the by-product of the anaerobic digestion process, can be used as a fertiliser on agricultural land. Currently the safe application of digestate is promoted through the PAS110 (WRAP 2008) and the Bio-fertiliser Certification Scheme (United Nations 1998). These outline an industrial specification to which producers can verify the quality of their digestate. Little research has been conducted to assess the impact digestate may have on local ecosystems, and in particular, soil species. Such impact could be of particular interest to those farmers who aim to encourage the presence of diverse soil biota to aid crop yields. This practice is widely encouraged and adopted by organic farmers (Blake 1990, Mader *et al.* 2002).

The chemical composition of digestate differs from its original feedstock by having a lower organic matter (OM) content, a higher ammoniacal nitrogen content and a higher pH (Kirchmann & Witter 1992, Wulf *et al.* 2002a, Clemens *et al.* 2006, Ernst *et al.* 2008a). These differences may potentially alter the way digestate is used as a fertiliser within both organic and conventional farming. As the properties of organic and synthetic fertilisers are different, and therefore are used in different ways, understanding the properties of digestate is important to maintain good nutrient management and to maximise crop yields.

Organic farmers heavily rely on the health of the soil ecosystem to ensure crop production and protection (Mader *et al.* 2002, Lampkin *et al.* 2008). Soil species facilitate the breakdown of organic nutrients within slurries and manures and convert them into their inorganic forms. The inorganic nutrients are then accessible to plants (Baghai *et al.* 2008). If digestate has a detrimental effect on the established biological ecosystems then there may be a reduction in the number of soil species that promote soil fertility. This may lead to fewer nutrients being released and a decrease in the soil fertility (Mader *et al.* 2002). This practice could therefore compromise the farmer's organic ethos of maintaining the health of the soil and promoting biodiversity. It may also potentially affect the crop yields and farmer's profits.

As the price of oil increases and the availability of phosphate decreases, conventional farmers may also consider using digestate as an alternative fertiliser (World Bank 2011).

Nutrients within chemical fertilisers are water soluble and are immediately available to plants. They are therefore only applied at peak growing periods to reduce the amount of nutrients lost through leaching. Digestate contains OM and some nutrients in an inorganic form. Soil biota is therefore still needed to breakdown OM and convert nutrients into accessible form. If conventional farmers are not aware of the chemical difference of digestate compared with slurry, they may encounter problems. For example a reduced yield may occur due to poorly timed digestate application or resulting in an incomplete OM breakdown. Farmers using digestate should therefore be aware of the condition of their soil biota and where possible, try to promote diversity to enable sufficient release of organic nutrients.

Earthworms play an important role sustaining soil fertility by their ability to turn and aerate soil, increase drainage and recycle nutrients (Syers & Springett 1984, Myers 2006, Jones *et al.* 2008). The application of chemicals may cause earthworm emigration or death leading to a reduction in the beneficial functions earthworms provide directly, and the associated effects on the ecosystem (Van Gestel 1992, Mader *et al.* 2002, Schaefer 2004, Hund-Rinke *et al.* 2005, Garcia *et al.* 2008).

Earthworms are excellent subjects to use for eco-toxicology experiments. They are highly sensitive to chemicals and can be easily maintained in the laboratory (Hogetsu *et al.* 1992, Stephenson *et al.* 1998). Earthworms use chemoreceptors to differentiate between food substrates and show dietary preferences (Laverack 1963, Bonkowski *et al.* 2000). A range of earthworm based protocols are available, each with their own benefits and problems. Generally earthworms are used to assess the effects of metals and pesticides through effects on a range of variables including behaviour, physiology, and ability to reproduce and survive (Jones & Hart 1998, Stephenson *et al.* 1998, Hund-Rinke & Wiechering 2001, Hund-Rinke & Kordel 2003, Schaefer 2004). There is opportunity to extend ecotoxicology work to examine organic contaminants with some modification to the ISO standards (ISO) (Van Gestel & Weeks 2004) (see section 1.3.iv for further discussion). Multiple tests can be used to ensure the results of the effects from digestate are robust and consistent over a number of variables.

Bioassay results can vary between species, and so to assess a chemical’s effect on an agricultural system, multiple species should be used. (Mataalvarez *et al.* 1993, Fitzpatrick *et al.* 1996, Lukkari *et al.* 2005). The species *Eisenia fetida* and *E. andrei* are primarily used for laboratory bioassays due to their low maintenance cost and high tolerance to laboratory conditions. As both of these species are epigeic earthworms the results may show a bias towards the behaviours of the epigeic functional group (See chapter 1.3.iv for details of earthworm functional groups). These species are not commonly found in agricultural fields and so could provide a limited insight into the effects digestate has on soil ecosystems. They may also be better adapted to survive in compost-like materials, such as soils treated with organic fertilisers, as frequently inhabit areas of high organic content (Edwards & Lofty 1972). For this reason, running experiments on a species more commonly found in agricultural fields could make the results more ecologically relevant (Lukkari *et al.* 2005).

Maintaining *Lumbricus terrestris* in the laboratory is difficult and therefore their use within bioassay experimentation is limited (Lowe & Butt 2005, ISO 2008). As *L. terrestris* is one of the key species found within agricultural fields and only periodically visit areas high in OM, the application of digestate may affect their behaviour and survival differently compared to *E. fetida.* In the laboratory earthworms are fed on decomposed horse and cattle manure and so, while high levels of composts may be detrimental, they can tolerate lower concentrations or higher concentrations in isolated areas, for example, surface cover (Lowe & Butt 2005). Also, due to the design of the bioassay chambers, *L. terrestris* are unable to practice the normal behaviour of burrowing to depths greater than 10 cm (Lowe & Butt 2005). By using both species in bioassays, the model species can verify that the protocol works, and *L. terrestris* can make the research more ecologically relevant.

When attempting to predict ecological impact within the soil, it is important to understand how digestate will be used. In particular, it is important to understand the effects different concentrations can have on earthworms. Potentially, the longer the digestate has been spread, the less effect it will have on earthworms due to a loss of volatiles (Banks *et al.* 2011a).

The main aim of this chapter is to assess what effect digestate application will have on the earthworms *E. fetida* and *L. terrestris* through multiple types of bioassay. These will be analysed in the light of the field experiments and be used to compliment the findings reported in chapter two. The main objectives are therefore to:

1) Assess the effect slurry and digestate made from a range of feedstock, has on earthworm behaviour using the ISO's (International Organisation for Standardization) two chamber Avoidance Behavioural Test (ABT) (ISO 2008).

2) Identify any species-specific choices between digestate and slurry using two earthworm species from different functional groups. This was first identified as potentially having an effect from the results of chapter two. Choices will be determined through both a ABT, and modified ISO earthworm tier one acute test (ISO 1993).

3) Identify whether the concentration and age of treatments have any effect on species preference. This will be measured through behavioural and physiological changes within two earthworm species.

4) Compare the suitability of the two species used for experimental analysis and their value within practical implications for testing agricultural chemicals. This will be based upon the success of the results from all the experiments performed within this chapter.

5) Identify potential long term effects caused by treatments in the event where digestate was to replace slurry application.

3.2 Materials and methods

3.2.1 Laboratory experiments

A range of methods were used to examine a number of variables. The results from these experiments can also be used in conjunction with some of the findings regarding earthworm behaviours in chapter two.

i) Test medium

All bioassays were run using commercially produced sterilised loam topsoil (pH7) purchased from B&Q (Southampton store- head office; Torrance House, Erskine, Renfrewshire, PA8 6AT). Commercially purchased soil is a recognised earthworm culture substrate (Langdon *et al.* 2003), as well as a standard medium for use in toxicology tests (Spurgeon *et al.* 2004). By exposing the treatments to a medium that is similar to natural field soil, the results can be better related to field conditions (Van Gestel & Weeks 2004, Edwards *et al.* 2009). Soil was dried, sieved (<3.25mm) and re-hydrated to 60% its water holding capacity (WHC) as recommended by ISO 17512- 1:2008 (ISO 2008), using either, only water (for the controls) or water in combination with treatments.

ii) Test organisms

Two species were used, *E. fetida*, (Figure 3.1a), and *L. terrestris* (Figure 3.1b). These were purchased from Wormbait.com, (Pine Trees Farm, Sowerby Bridge, UK). Only adults and sub-adults were used.

The individual biomass for each earthworm ranged between 0.3 g to 0.6 g for *E. fetida* (Mean = 0.38 g ± 0.003 N = 1413) and 3 g to 6 g for *L. terrestris* (Mean = 4.88g ± 0.60 N = 752). *E. fetida* were used to ensure the validity of the protocol and allow a comparison between bioassays previous conducted in the literature. They were kept in control soil in an Environmentally Controlled Room (ECR) set at 20ºC ± 2ºC, 12:12 light to dark, and allowed to acclimatise for at least one week. *L. terrestris* were used here as they are commonly found in agricultural fields and are considered a good test species (Fitzpatrick *et al.* 1996, Lukkari *et al.* 2005). They were kept in control soil in an ECR set at 18ºC ± 2ºC 12:12 light to dark, and allowed to acclimatise for at least one week.

a) b)

Figure 3.1. a) *Eisenia fetida* (Savigny 1826) and b) *Lumbricus terrestris* (Linnaeus 1758). Individuals were obtained commercially and kept in species specific controlled environments. Adults and sub-adults were identified as having or showing signs of the clitellum developing (Sims & Gerard 1985).

iii) Details of treatments

Digestate and slurry sourced from a range of locations and produced from a variety of feedstock were collected and frozen until a few days prior to the experiment to reduce potential chemical changes. After thawing, treatments were stored at 4ºC in sealed, plastic containers. Chemical compositions for each treatment used within this chapter are outlined in table 3.1 and table 3.2. Total Kjeldahl Nitrogen (TKN) and ammoniacal nitrogen for each treatment were determined using the Kjeldahl method (Webb *et al.* 2004). Percentage dry weights (DW%) were calculated by subtracting water loss from samples oven heated to 105°C for 8 hours (DECC 2009b) and the total organic carbon was calculated by baking dried samples in a furnace for 2 hours at 660°C. The pH was measured using a Hydrus 400 pH meter.

3.2.2 Toxicity experiments

Lethal Dose 50 (LD_{50}) for digestate and slurry were identified after three, six and 14 days of treatment. Measurements at three days were used to match the two-chamber bioassay work for *L. terrestris*, and measurements at six and 14 days were ,made in line with other publications (Zhou & Liang 2003, Xiao *et al.* 2004). Lethal Time 50 (LT_{50}) was calculated for a range of TKN concentration (See table 3.2 for details).

Preliminary experiments were used to determine appropriate concentrations. These needed to include at least one concentration where 100% mortality would be reached. For

E. fetida five concentrations were used; 21.25 kg N ha^{-1}, 42.5 kg N ha^{-1}, 85 kg N ha^{-1}, 170 kg N ha^{-1} and 340 kg N ha^{-1}. This range was used to represent realistic concentrations farmers may use, and with one concentration over the maximum spread of 170 kg N ha^{-1}. A large number of earthworms died when exposed to the final concentration of 340 kg N ha^{-1}, compared with the 170 kg N ha^{-1} concentration. So as to make the LD_{50} and LT_{50} calculations more precise two additional concentrations of 220 kg N ha^{-1} and 280 kg N ha^{-1} were included. For *L. terrestris,* the concentrations used were 85 kg N ha^{-1}, 170 kg N ha^{-1}, 220 kg N ha^{-1}, 280 kg N ha^{-1} and 340 kg N ha^{-1}, preliminary experiments having found no effect on earthworm behaviour at concentrations of 42.5 kg N ha^{-1}. Concentrations above 340 kg N ha^{-1} were not used as this would not be representative of actual exposures in the field. Concentration 220 kg N ha^{-1} and 280 kg N ha^{-1} were also included based upon the findings from the *E. fetida* bioassays. Adult individuals of *L. terrestris* (Mean = 5.84 g ± 1.29 N = 352) and *E. fetida* (Mean = 0.41 g ± 0.006 N = 563) were used for this experiment.

Top soil (400 g DW) was mixed with slurry or digestate at each of the concentrations to ensure the earthworms had an even exposure, and to reduce potential anaerobic conditions that may occur from applying the treatment to the surface alone (Mitchell 1997). Square plastic containers were used (13 cm x 13 cm x 7 cm = 0.6 l), each covered with a plastic lid with a meshed covered hole to allow light and air exchange. Eight to 10 *E. fetida* and six or seven *L. terrestris* individuals were weighed and introduced to each container, with 4 repeats for each concentration. Over 30 individuals were used for each concentration. The number in each pot depended on the size of the earthworms to minimise over-crowding. *E. fetida* trials were incubated in an ECR set to 20°C ± 2°C, and trials on *L. terrestris* were incubated at 18°C ± 2°C. A 24hr light setting was used for both to ensure maximum exposure to the soil (ISO 2000). Pots were checked daily for dead individuals and the number remaining alive was recorded. Dead individuals were removed and disposed of. Concentrations with relatively high survival rates, but that have some effect on the earthworms at the highest concentration, were identified and used as the concentrations for the for two-chamber bioassays.

The Probit Analysis on Minitab ® Statistical Software v16.1.0 (Minitab Inc., State College, PA., USA) was used to calculate the LD_{50} and LT_{50} for each treatment. Results were then compared between treatments and species by comparing their confidence intervals (CI) (Girling *et al.* 2010).

3.2.3 Two-Chamber Avoidance Behaviour Tests (ABT' s)

Avoidance responses were tested using the two chamber avoidance test as described in the ISO 17512- 1:2008 (ISO 2008). Circular plastic containers, 17.5 cm in diameter, were filled with 700g DW of top soil. This led to a depth of 6 cm within each container (Figure 3.2).

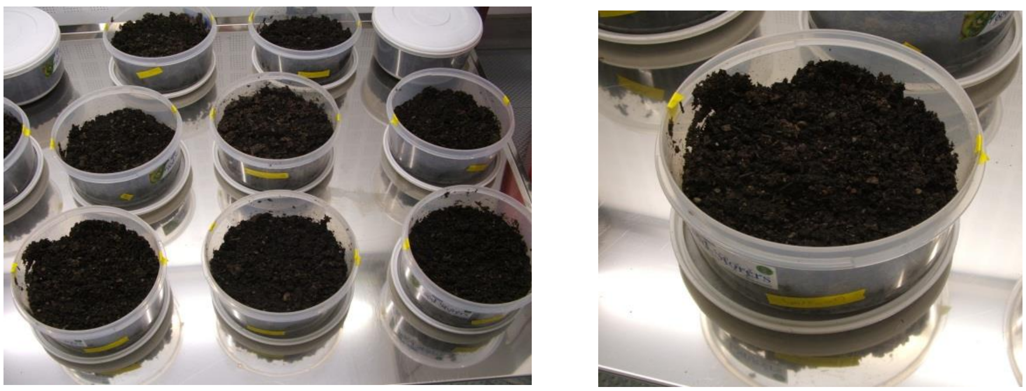


Figure 3.2. Plastic circular container (2l) used for earthworm ABT's (plastic film cover not yet attached). The yellow tabs indicate the dividing line between treatments, and the point where earthworms were introduced. Containers were arranged in a random order of treatment and concentration on the shelf, with containers rotated 72° with each repeat.

Treatments were mixed into soil in a bucket. Chambers were divided into two using a cardboard divider with treated soil added into one side, and non-treated soil introduced to the other. This prevented mixing of the two sides during preparation. Although a homogenous concentration of digestate is unlikely to occur in the field as created within the bucket, it was done here to maximise the earthworm's exposure to the treatment. The divider was then removed and 10 earthworms of one species (either *E. fetida,* (total used within these trials N = 400;) or *L. terrestris,* (total used within these trials N = 400)) were placed into the indentation created by the divide. The chamber was covered with a clear plastic film, with air holes to prevent earthworms from escaping, and placed on the same shelf to ensure equal light distribution. Earthworms were weighed before and after the bioassays.

Boric acid (1450 mg kg^{-1} DW soil) was used as a positive control. The concentration for this was calculated after preliminary trials to ensure a high level of repulsion, without toxic effects to the earthworms (preliminary range from 750 mg kg^{-1} DW soil – 2500 mg kg^{-1} DW soil). A concentration was deemed unsuitable when the death rate exceeded 10% as this would make the control void (ISO 2008). The boric acid was used here at a higher concentration than the recommended ISO concentration of 794 mg kg^{-1} for an EC50 response in Alberta black chernozem soil. This was to ensure a >80% repulsion effect was achieved and accounted for the differences between the two types of soil (ISO 2008). In addition a control was used; containing two sides of untreated soil to ensure earthworm movement was random within the chambers.

In accordance with the ISO standards (ISO, 2008) bioassays using *E. fetida* were incubated in an ECR at 20 ± 2°C on a 12:12 hr dark: light setting for 48 hours. *L. terrestris* were kept in an ECR at 18 ± 2°C on a 12:12 hr dark: light setting for 72 hours. The results were considered to be more reliable when *L. terrestris* had longer exposure time compared to *E. fetida* (Fitzpatrick *et al.* 1996)*.* After the allotted time, the number of earthworms on each side of the chambers were counted and weighed to an accuracy of 0.001g. For individuals located across the dividing line, the count was given to the side containing the head. No count was given to individuals found dead, and these worms were not weighed. Each experiment treatment had 5 repeats (N = 50).

Two bioassays were performed; the first tested earthworm choice between slurry and digestate at three levels of nitrogen concentration identified as suitable from the LD_{50} studies (please see above for details); high = 170 kg N ha^{-1}, medium = 85 kg N ha^{-1}, low = 42.5 kg N ha^{-1}. Two ages of application were used; new = treatment mixed into soil less than 3 hours prior the start of the experiment, old = treatment mixed into soil one week and then re-hydrated to its original moisture content prior to the experiment. Each set of trials had five repeats and were performed on both earthworm species. See table 3.1 below for details of the treatments used for these bioassays.

Table 3.1. Details of the treatments used in the two chamber ABT trials. The same source of organic dairy slurry was used with before (raw slurry), and after the digestion process (digestate). (VS = volatile solids from dried sample, DW = dry weight)

Treatment	TKN (mg l^{-1})	Ammoniacal N (mg l^{-1})	DW (%)	pH	%VS
Raw slurry	1853	864	3.96	8.01	0.10
Digestate	2059	1046	1.27	7.24	0.03

The second experiment tested earthworm choices between treatments from a range of digestate sources at a standardised TKN concentration of 170 kg N ha^{-1}, against untreated soil. Here, 170 kg ha^{-1} was used in one dose to estimate maximum possible response from the earthworms, although this may be higher than that of exposure in realistic agricultural practice. Control soil was made up to 60% of the soils water holding capacity (WHC) by mixing 189 ml of water with 350 g DW topsoil. For the treated side, water was used to make up the treatment volume to 189 ml mixed into 350 g DW topsoil. See table 3.2 for details of treatments used for these bioassays.

Table 3.2. Details of the treatments used in the bioassays of treatment versus control. Test species *E. fetida* with Animal Behaviour Test (ABT) bioassays conducted in circular two chamber containers. Loading rate for each treatment was equal to 170 kg N ha^{-1}. Treatment 1 & 2 sourced from the University of Southampton, Civil Engineering and the Environment. Treatments 1 & 2 differ only with regard to trace elements added. Treatments 3 - 5 were sourced from externally run digesters. Treatments 5 & 6 were sourced from the same farm and represent before and after digestion.

Treatment		Treatment details	TKN (mg l^{-1})	%VS	pH
Digestate	1	Food waste with trace elements	9582	8.22	7.88
	2	Food waste, no trace elements	9650	7.85	7.95
	3	Maize and cattle slurry	6523	5.48	8.92
	4	Community food waste	7915	5.52	8.82
	5	Organic cattle digestate	1940	1.73	7.58
Raw material	6	Organic raw cattle slurry	1797	4.04	6.77
	7	Conventional raw cattle slurry	4025	11.24	7.17

For both ABT experiments, treatments were assessed on their potential of having a habitat function if >80% of the earthworms were found inhabiting one side of the chamber. A G-test for heterogeneity was performed for each treatment to ensure data could be pooled between repeats (Fowler *et al.* 1998). This was not the case for all data, and where unsuitable, the results have been discussed separately. For suitable data, a pooled G-test was used to test whether treatment effect on earthworm distribution differed from random across the two chambers. A two sample T-test was used to determine the changes in biomass between treatments and the biomass of the control earthworms for both *E. fetida*, and for *L. terrestris* (Fowler *et al.* 1998). In addition, a Generalised Linear Model (GLM) was used to identify effects of treatment concentration, age and the interaction of concentration and age on the mass changes of earthworms during the bioassays. All statistics were performed using Minitab ® Statistical Software v16.1.0 (Minitab Inc., State College, PA., USA).

3.3 Results

3.3.1 Toxicity tests (LD_{50} and LT_{50})

As the TKN concentration increased, time to reach LT_{50} decreased for both earthworm species (Table 3.3). The species differed in their responses to the two treatments at a concentration of 280 kg N ha^{-1}. For this, the upper and lower confidence intervals (CI) for the LT_{50} between the two treatments no longer overlapped for either species. For *E. fetida* the LT_{50} was lower when exposed to digestate compared with exposure to slurry. The reverse was seen in *L. terrestris,* with earthworms having a longer LT_{50} in slurry treated soil, compared with digestate treated soil. At concentrations of 220 kg N ha^{-1} and below, treatment type did not have an effect on the earthworms' LT_{50}.

Table 3.3. LT_{50} values in days for *E. fetida* and *L. terrestris* at 5 concentrations of digestate and slurry, ± SE with confidence intervals (CI) below in brackets. Values with matching uppercase letters were significantly different between treatments (within species) and those values with matching lowercase letters were significantly difference between species (within treatment). Statistical difference defined as values where there is no overlap between their CI (Girling *et al.* 2010).

	E. fetida		*L. terrestris*	
TKN	Slurry	Digestate	Slurry	Digestate
85	51.0 ± 21.1 (29.8 - 1701.7)	50.5 ± 20.9 (29.6 - 1687.7)	55.9 ± 26.2 No CI	57.9 ± 27.5 No CI
170	39.3 ± 10.8 (26.7 - 104.5)	39.1 ± 10.7 (26.5 - 103.4)	35.6 ± 7.6 (25.9 - 67.6)	29.5 ± 5.9 (21.8 - 54.5)
220	2.1 ± 0.2 a (1.7 - 2.5)	1.7 ± 0.2 b (1.3 - 2.1)	34.1 ± 7.7 a (24.4 - 70.2)	35.2 ± 8.2 b (25.0 - 73.4)
280	0.4 ± 0.2 Ac (-0.1 - 0.7)	1.3 ± 0.1 Ad (1.1 - 1.5)	21.5 ± 2.0 Bc (18.3 - 26.9)	13.3 ± 1.0 Bd (11.6 - 15.8)
340	0.8 ± 4.1 No CI	1.8 ± 3.6 No CI	18.8 ± 1.4 C 16.5 - 22.2	9.3 ± 0.6 C 8.2 - 10.6

Concentration had a species specific effect. *L. terrestris* were able to survive significantly longer in soils treated with either of the treatments at the concentrations equal to and above 220 kg N ha^{-1} compared to *E. fetida.* Data were also analysed according to a common mass of g^{-1} live weight (LW) (Table 3.4).

Table 3.4. LT_{50} values in days for *E. fetida* and *L. terrestris* set as g^{-1} live weight (LW) earthworm at 5 concentrations of digestate and slurry, ±SE with confidence intervals (CI) below in brackets. Values with matching uppercase letters were significantly different between species (within treatments) and those values with matching lowercase letters were significantly difference between treatments (within species). Statistical difference defined as values where there is no overlap between their CI (Girling *et al.* 2010).

	Slurry		Digestate	
TKN	*E fetida*	*L. terrestris*	*E. fetida*	*L. terrestris*
85	132.7 ± 54.9 (77.7 - 4431.1)	11.5 ± 5.4 No CI	131.6 ± 54.4 (77.1 - 4394.8)	11.9 ± 5.6 No CI
170	141.6 ± 43.4 A (69.4 - 272.0)	7.3 ± 1.6 A (5.3 - 13.9)	60.5 ± 15.1 B (69.0 - 269.3)	6.0 ± 1.2 B (4.5 - 11.2)
220	5.5 ± 0.5 (4.5 - 6.4)	7.0 ± 1.6 (5.0 - 14.4)	4.5 ± 0.5 (3.5 - 5.4)	7.2 ± 1.7 (5.1 - 15.1)
280	1.0 ± 0.4 C a (-0.2 - 1.7)	4.4 ± 0.4 C b (3.8 - 5.5)	3.4 ± 0.2 a (2.9 - 3.8)	2.7 ± 0.2 b (2.4 - 3.2)
340	2.1 ± 10.7 No CI	3.9 ± 0.3 c (3.4 - 4.6)	4.7 ± 9.3 No CI	1.9 ± 0.1 c (1.7 - 2.2)

By standardising the earthworm species by g^{-1} LW, *E. fetida* had a higher survival rate at lower concentrations of treatment, although this was only significant at a concentration of 170 kg N ha^{-1}. Comparisons below this concentration could not be done as there were no CI's available for *L. terrestris* at 85 kg N ha^{-1}. The LT_{50} were similar between the two species at 220 kg N ha^{-1} although *L. terrestris* had much larger CI and are therefore more variable and less predictable in their responses. At the highest slurry concentrations *L. terrestris* had a larger LT_{50} than *E. fetida,* and at the highest digestate concentrations, *E. fetida* had a larger LT $_{50}$ than *L. terrestris. E. fetida* had a very large LT_{50} at low treatment concentrations, which dropped quickly at 220 kg N ha^{-1}, while the LT50 for *L. terrestris* was relatively low and, as concentration declined, had a steady decline in its LT50 for slurry ($F_{1,4}$ = 47.29, P <0.01) and digestate ($F_{1,4}$ = 25.50, P< 0.05).

E. fetida had a lower LD_{50} for both digestate and slurry compared with *L. terrestris. E. fetida* require less than half the concentration of that needed by *L. terrestris,* to reach their LD_{50} (Table 3.5).

Table 3.5. LD_{50} values in kg N ha^{-1} for *E. fetida* and *L. terrestris* for 3, 6 and 14 days after application ± SE Confidence intervals (values in brackets) for between treatments all overlapped, suggesting no significant differences. All values between species overlapped, therefore no significant difference between the species.

	E. fetida		*L. terrestris*	
Day	Slurry	Digestate	Slurry	Digestate
3	208 ± 5 (199 - 217)	192 ± 4 (184 - 201)	564 ± 94 (444 - 1006)	524 ± 85 (416 - 925)
6	183 ± 6 (171 - 195)	172 ± 6 (160 - 184)	502 ± 61 (414 - 708)	413 ± 43 (350 - 554)
14	181 ± 6 (169 - 193)	171 ± 6 (158 - 183)	406 ± 31 (356 - 489)	322 ± 21 (286 - 374)

Again, to normalise the mass differences between species, the values were standardised to g^{-1} Live Weight (LW) (Table 3.6).

Table 3.6. LD_{50} values in kg N ha^{-1} g^{-1} of live weight earthworm for *E. fetida* and *L. terrestris* for 3, 6 and 14 days after application ±SE. None of the confidence intervals (values in brackets) for between species within treatments overlapped, suggesting significant differences between the species for all treatment concentrations.

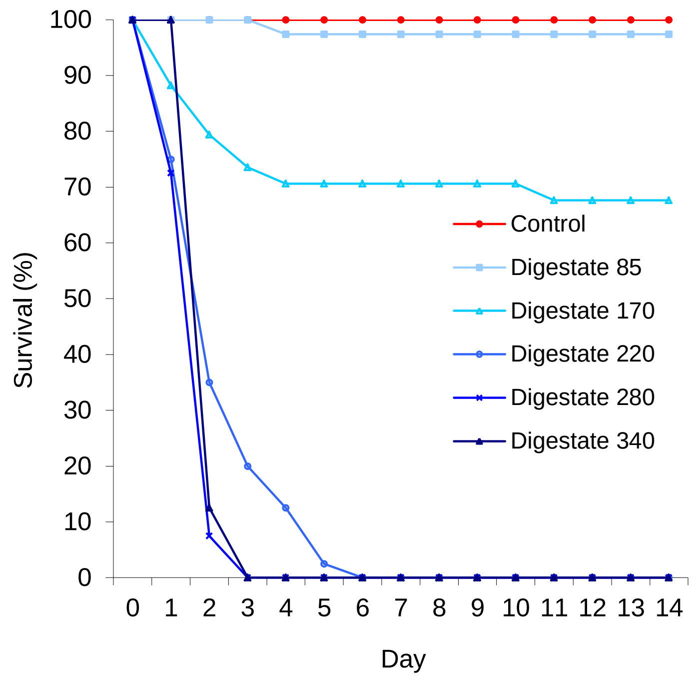
	Slurry		Digestate	
Day	*E. fetida*	*L. terrestris*	*E. fetida*	*L. terrestris*
3	542 ± 12 A (518 - 565)	116 ± 19 A (91 - 207)	501 ± 11 B (478 - 523)	108 ± 18 B (85 - 190)
6	477 ± 156 C (445 - 507)	103 ± 13 C (85 - 145)	449 ± 16 D (415 - 480)	85 ± 9 D (72 - 114)
14	472 ± 16 E (441 - 503)	83 ± 6 E (73 - 100)	445 ± 16 F (412 - 476)	66 ± 4 F (59 - 77)

E. fetida were able to tolerate higher concentrations of both treatments per g^{-1} Live Weight compared with the *L. terrestris* for all of the three time points considered. The dose required to kill 50% between treatments did not significantly differ within the species.

E. fetida showed a rapid response to the treatment, with a sharp drop in survival in slurry and digestate concentrations of 220 kg N ha^{-1} and above (Figure 3.3). Statistics could not be performed on treatment concentrations of 280 kg N ha^{-1} and 340 kg N ha^{-1} due to the rapid mortality. Log transformed data from slurry treatments at a concentration of 220 kg N ha^{-1} had a negative correlation with day for the first 7 days (until 100% death) ($F_{1,7}$ = 178.72, P <0.001) and an average reduction in survival of 14.49% per day. Log transformed digestate data at a concentration of 220 kg N ha^{-1} showed a negative correlation with day for the first 6 days (until 100% death) ($F_{1,6}$ = 100.73, P <0.001) and an average reduction in survival of 16.70% per day.

The number of surviving of *L. terrestris* decreased at a steady rate at the higher concentrations of digestate treatment (Figure 3.4). At 280 kg N ha^{-1} of digestate, there was a negative correlation with time, ($F_{1,14}$ = 163.28, P <0.001) with a decline in survival of 4.33% each day. For 340 kg N ha^{-1} of digestate, there was a negative correlation with time ($F_{1,14}$ = 173.14, P <0.001) with a drop in survival of 5.66% each day. None of the concentrations for digestate or slurry resulted in a 100% mortality in *L. terrestris.*

a)



b)

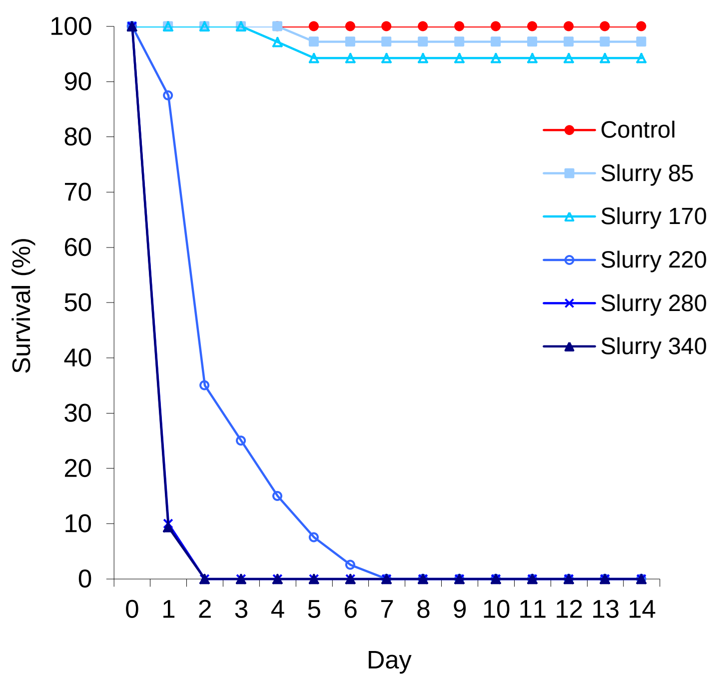
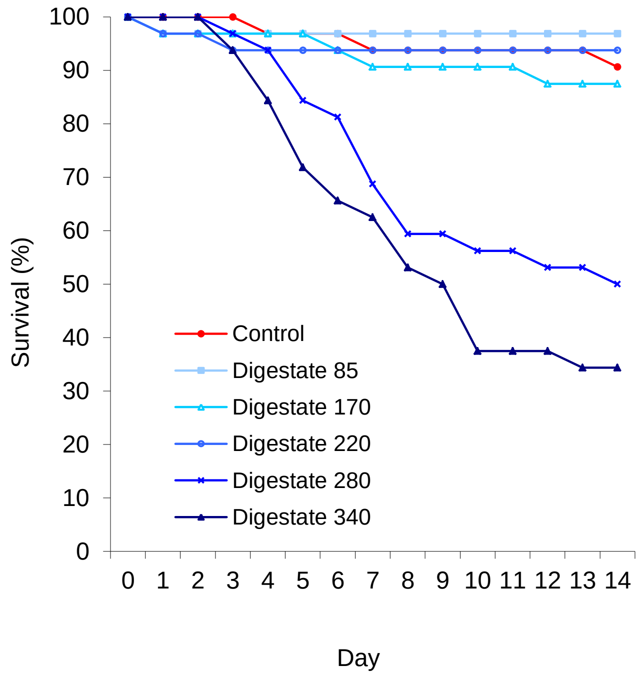


Figure 3.3. Survival curves of *E. fetida* after 14 days at 5 concentrations of treatment for a) digestate and b) slurry. Values in kg N ha^{-1}. Results for concentrations for 42.5 kg N ha^{-1} and 28.25 kg N ha^{-1} are not shown due to having similar results as 85 kg N ha^{-1}.

a)



b)

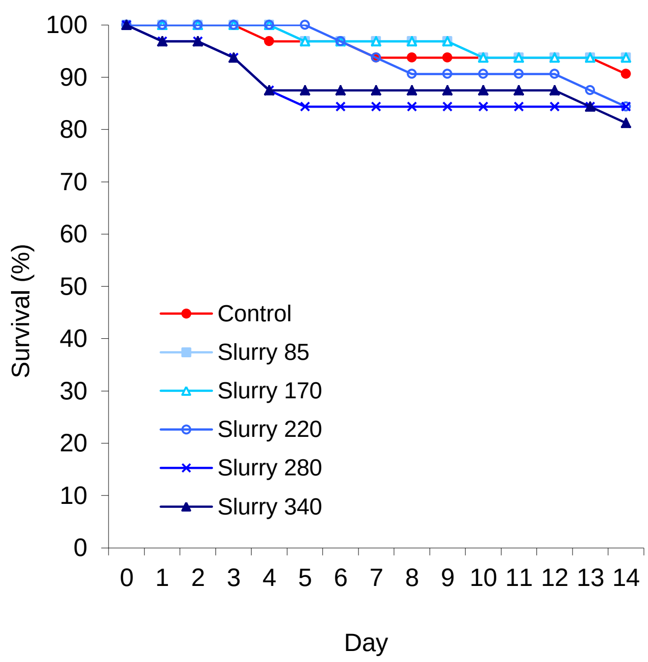


Figure 3.4. Survival curves for *L. terrestris* after 14 days at 5 concentrations of treatment for a) digestate and b) slurry. Values in kg N ha^{-1}.

3.3.2 Avoidance behaviour tests

i) Bioassays using E. fetida

G-tests were performed on each treatment to ensure pooling was permitted. From the results of this, only 4 tests were suitable for pooled G-test analysis. The data that were not suitable were due to the earthworms clumping together. *E. fetida* had an overall avoidance for newly applied slurry (or attraction towards the digestate) at the highest concentration of TKN (G_1 = 8.617, P <0.01). They were attracted to old slurry at the medium concentration (or repulsed by digestate) (G_1 = 8.22, P <0.01). They also significantly avoided boric acid (G_1 = 24.31, P <0.001) (Figure 3.5). The blank control demonstrated that without treatment, random earthworm distribution was achieved. No other experiment qualified for analysis, as they did not satisfy the G-test for heterogeneity. This suggests distribution was random and there were no effects from the treatments.

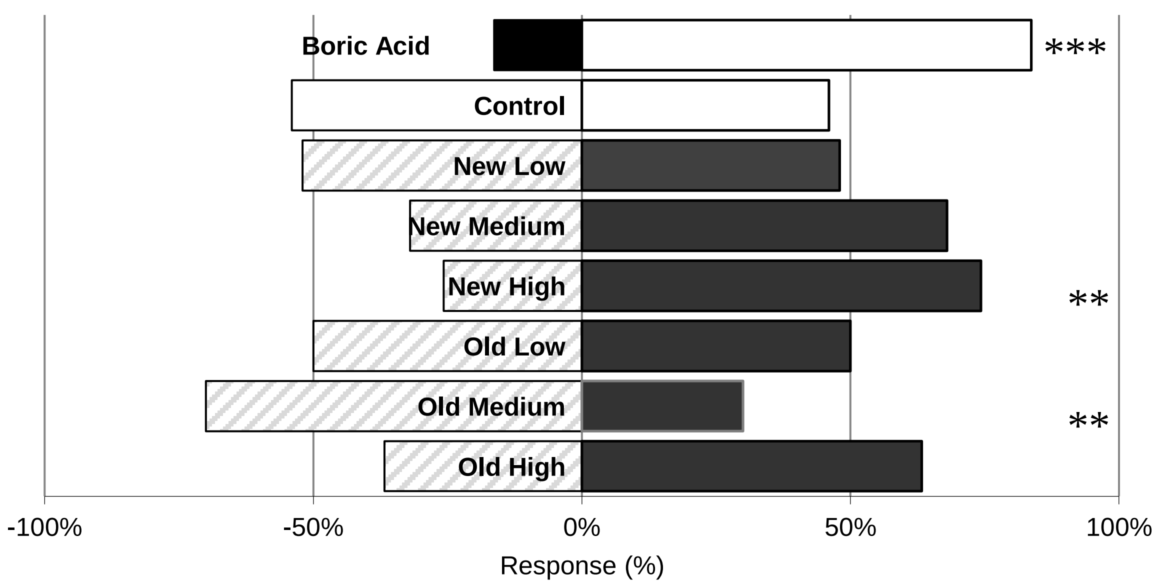


Figure 3.5. Choice between digestate and slurry treated soils for three concentration of TKN and two ages of treatment application using *E. fetida.* Dark grey= soil with digestate; stripy = soil with slurry; white = control soil; black = soil with boric acid. ***P <0.001 ** P <0.01.

On average, earthworms gained mass during the bioassay, except in the high new concentration (Figure 3.6). For this average mass was reduced, although this was not significant compared with the earthworm mass changes in the control treatments (T_4 = 2.47, P =0.07). Earthworms in the treatment old low significantly increased their mass compared to those in the control treatment (T_5 = -2.59, P <0.05). No other treatment differed significantly from the earthworm mass changes in the control. Change in earthworm mass after 48 hours was affected by the age of the treatment ($F_{1,24}$ = 11.02, P <0.01) and the concentration ($F_{2,24}$ = 7.97, P <0.01), but there was no effect from the interaction between age and concentration ($F_{2,24}$ = 1.41, P =0.26).

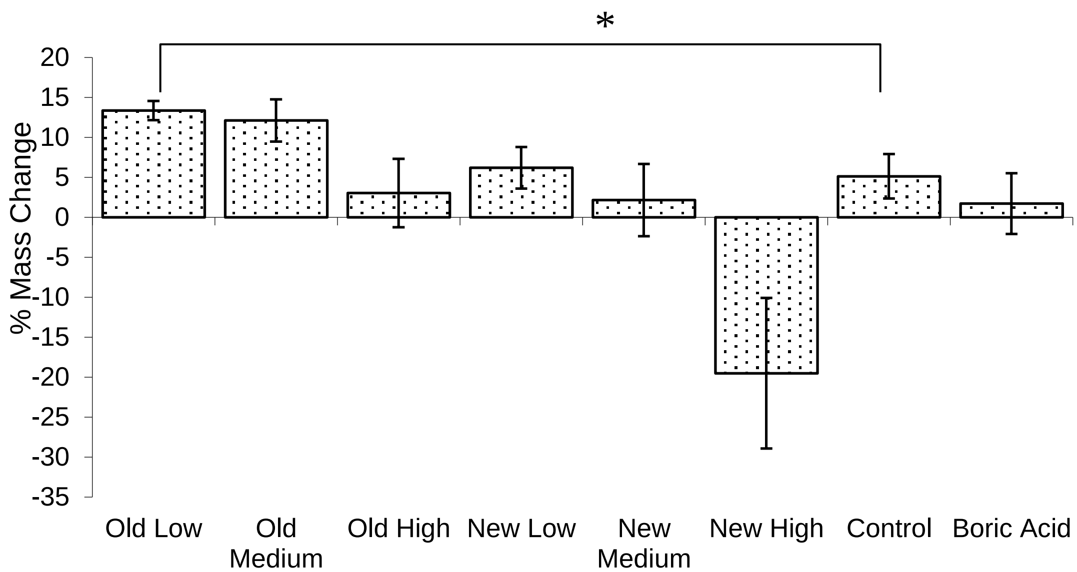


Figure 3.6. Percentage mass change in *E. fetida* over 48hr ABT bioassay for three concentrations at two ages of treatment application. All treatments had a positive effect on earthworm mass, except for high new treatments which had a negative effect on earthworm mass. *P <0.05

ii) Bioassays using L. terrestris

G-tests for heterogeneity for each experiment were carried out. All were suitable for pooling. Boric acid had a suitable repulsion effect on *L. terrestris* (G_1 = 6.63, P = 0.01), and the blank control demonstrated an even distribution between the chambers (G_1 = 0.020, P = 0.89). There was a repulsion effect from the digestate treatment (or attraction towards slurry) seen at the highest concentration (G_1 = 10.12, P <0.01) (Figure 3.7). No other treatment had an effect on earthworm distribution (New medium; G_1 = 3.49, P = 0.06, new low; G_1 = 10.12, P = 0.15, old high; G_1 = 0.79, P = 0.36, old medium; G_1 = 2.91, P = 0.09, old low; G_1 = 1.73, P = 0.19).

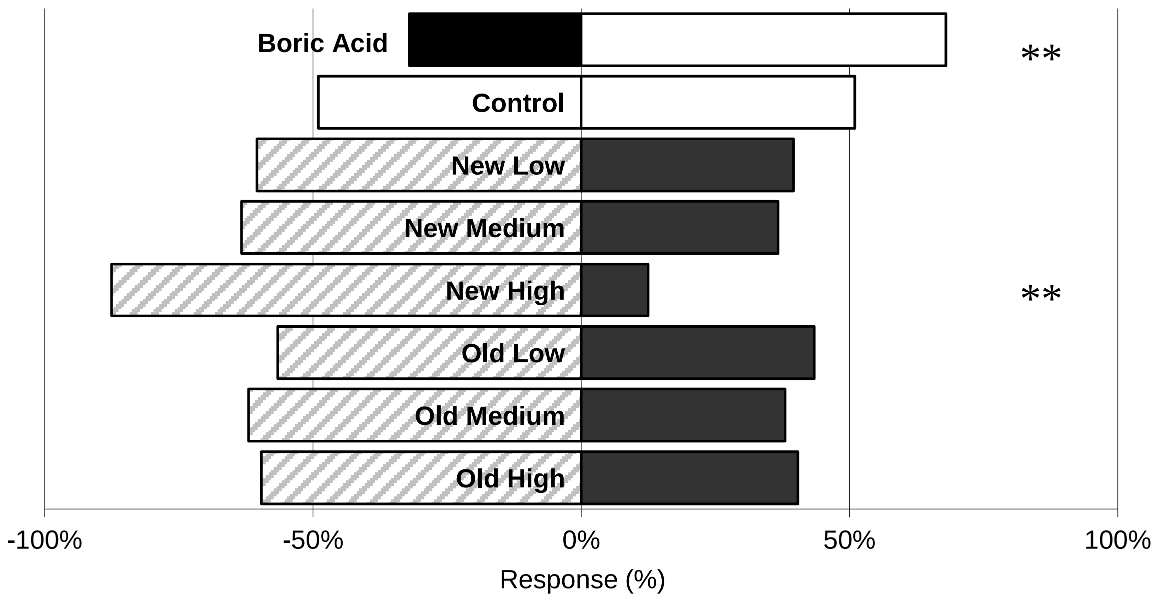


Figure 3.7. Choice between digestate and slurry using *L. terrestris* at three concentrations and two ages of application. Dark grey= soil with digestate; stripy = soil with slurry; white = control soil; black= soil with boric acid. ***P <0.001 ** P <0.01 *P <0.05

On average, earthworms lost mass during the bioassays, including in the control, except within the old medium (Figure 3.8). Of these, only earthworms within the new high treatment lost significantly more mass than earthworms in the control trial (T_4 = 3.21, P <0.05). Change in earthworm biomass was affected by both the age of treatment ($F_{1,24}$ = 7.44, P <0.05), and the concentration of the digestate ($F_{2,24}$ = 5.09, P <0.05). Interaction between age and concentration had no effect ($F_{2,24}$ = 1.73, P =0.20).

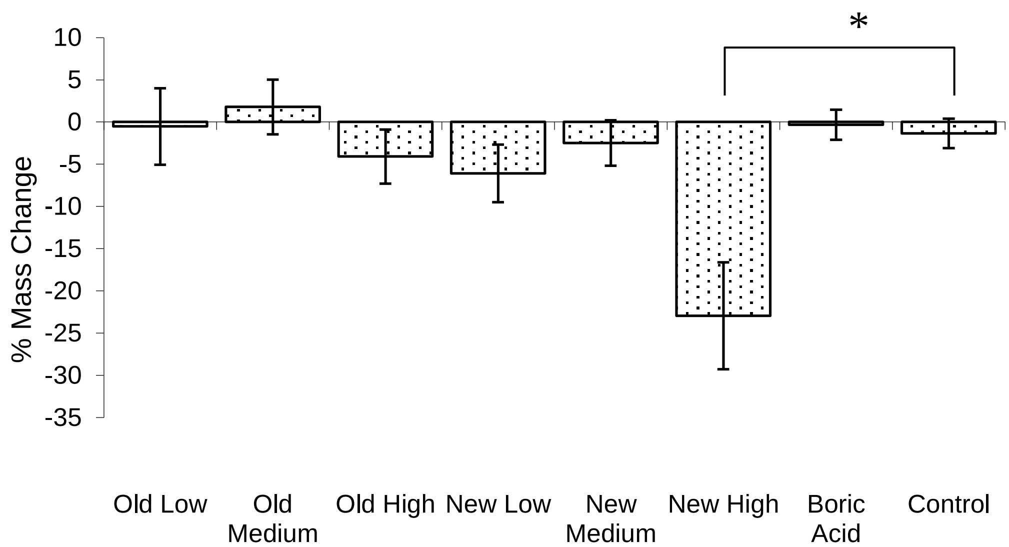


Figure 3.8. Percentage mass change in *L. terrestris e*arthworms after 72 hour bioassay. Error bars represent ± SE. Only old medium treatments had a positive effect on earthworm mass. ***P <0.001 ** P <0.01 *P <0.05

iii) Choice bioassays between control and treated soils

All treatments were suitable for pooled G-test analysis. Only *E. fetida* were used within this analysis due to the high mortality seen in the bioassays using *L. terrestris* at 170 kg N ha^{-1}. *E. fetida* showed an overall avoidance for all digestate and slurry treatments at 170 kg N ha^{-1} (Figure 3.9) (Food waste with additives χ^2_1 = 19.01, P <0.001, Food waste no additives χ^2_1 = 19.01, P <0.001, Slurry/maize digestate χ^2_1 = 19.01, P <0.001, community food waste χ^2_1 = 19.01, P <0.001, organic digestate χ^2_1 = 17.11, P <0.001, organic slurry χ^2_1 = 15.31, P <0.001, conventional slurry χ^2_1 = 19.01, P <0.001, control χ^2_1 = 0.01 P=1, boric acid χ^2_1 = 13.61, P <0.001). Both the boric acid and control worked as predicted with boric acid showing an approximate 9:1 ratio of avoidance, and the control of approx. 5:5 ratio of avoidance.

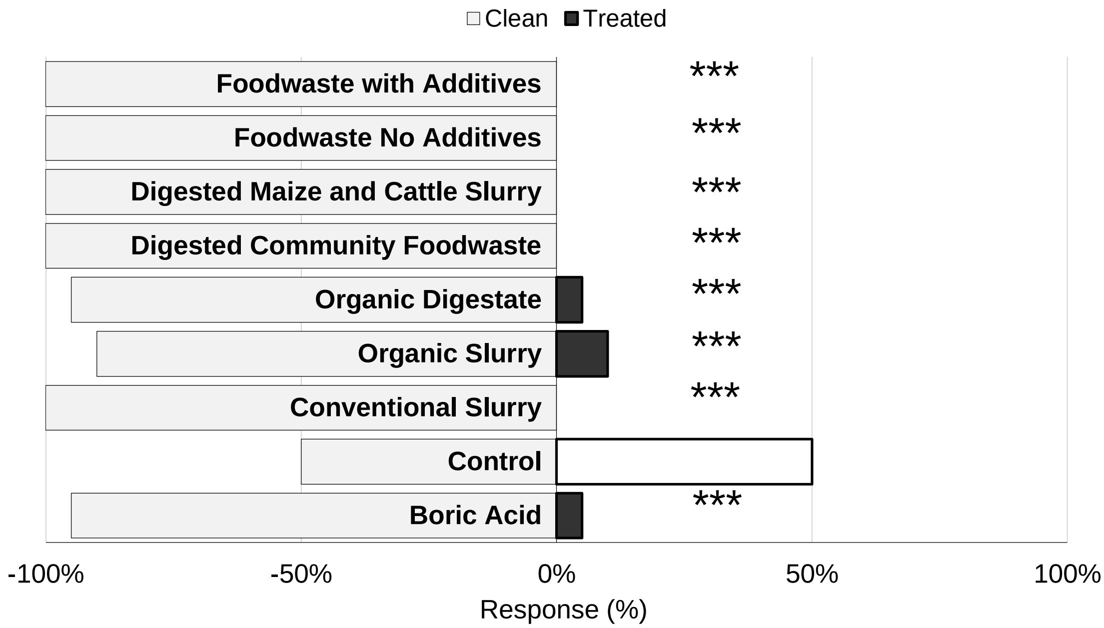


Figure 3.9. Earthworm avoidance behaviour responses towards soils treated with slurry and digestate from a range of feedstock types. The application of all treatments had a greater than 80% repulsion, suggesting application of all treatments had a habitat functional effect on earthworms (N = 50). Both control substances reported expected results. P <0.001***

The average earthworm mass increased during the experimental period for all treatments (Figure 3.10) with no significant differences when compared to the control.

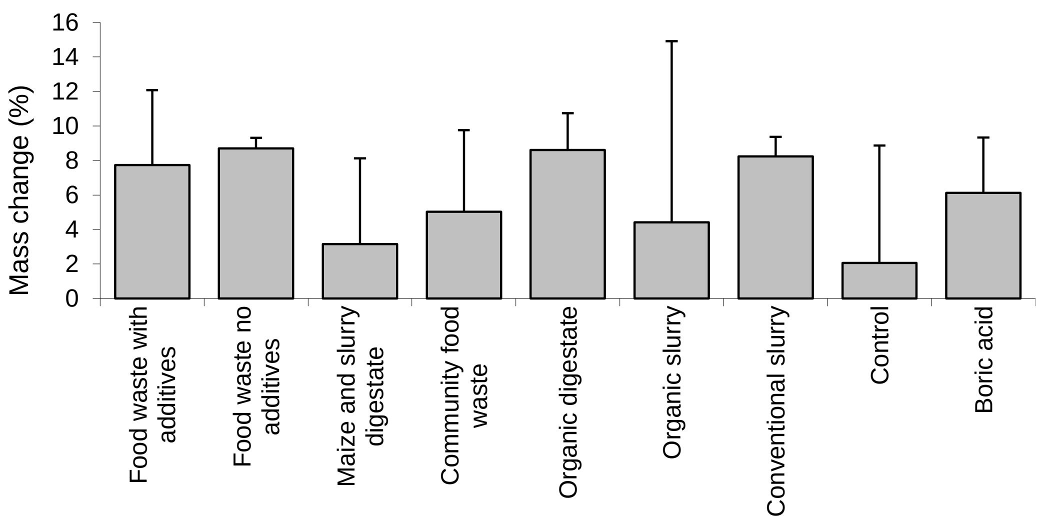


Figure 3.10. Change in *E. fetida* mass over the 48 hour period of the bioassays. Treatments vary according to the feedstock used to make them. Each was used at a concentration of 170 kg N ha^{-1}. Bars represent +SE (N = 30).

3.3.3 Births and deaths within trials

After the toxicity trials were complete, the number of cocoons found from each treatment for *E. fetida* was recorded (Figure 3.11). Within the digestate treatments, an increase in TKN resulted in a decrease in the number of cocoons found ($F_{1,4}$ = 15.83, P <0.05). Above 220 kg N ha^{-1}, no more cocoons were found. No cocoons were found in the *L. terrestris* containers after the 14 days.

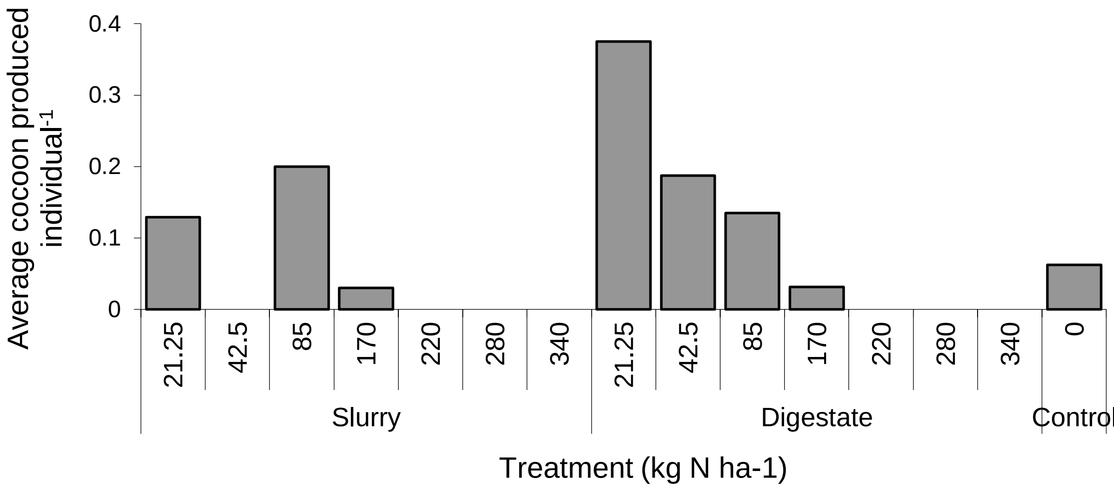


Figure 3.11. Total number of cocoons collected after 14 days from *E. fetida* toxicity trials. Seven concentrations of digestate and slurry were used,

L. terrestris appeared more likely to die during the avoidance behaviour tests between slurry and digestate compared with *E. fetida* (Figure 3.12), although this was not significantly different (T_9 = -0.78, P = 0.46). The daily mortality rates between the two species would be even smaller as the *L. terrestris* trials were 50% longer. A high number of dead individuals were found in both species in the high new treatment. There was also a steady rate of mortality seen during the LD_{50} / LT_{50} trials for the control pots of *L. terrestris,* ($F_{1,14}$ = 78.13, P <0.001) from 32 to 28, while *E. fetida* had 0% mortality after 14 days.

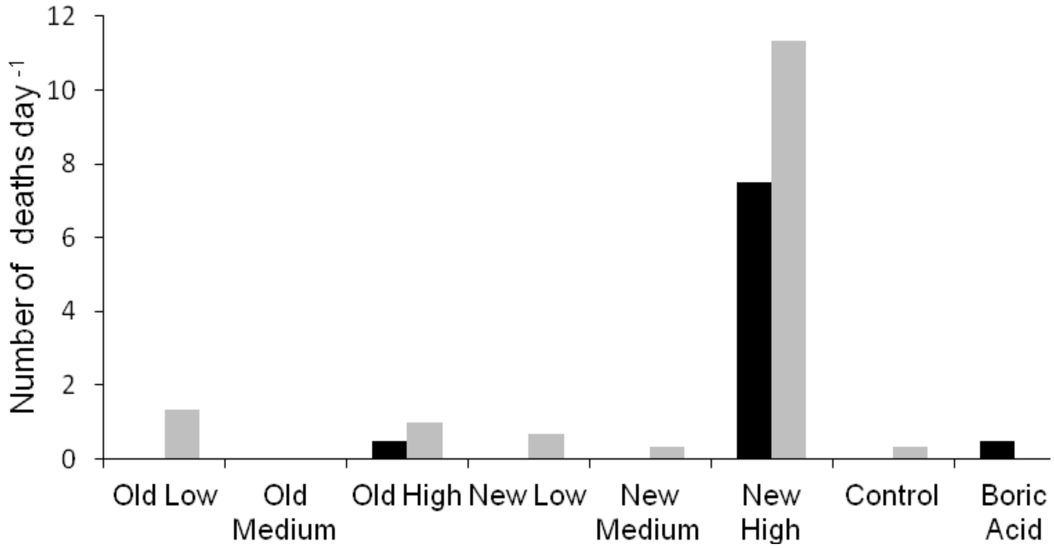


Figure 3.12. Number of individual deaths day^{-1} for each ABT bioassay. Bioassays for *L. terrestris* ran for 72 hours, and *E. fetida,* bioassays ran for 48 hours. Mortalities were higher than expected from previous toxicity work. Same number of earthworms for each species was used in each trial. Black= *E. Fetida,* grey= *L. terrestris.*

3.4 Discussion

Earthworms demonstrated a behavioural response to soils treated with slurry and digestate at and above concentrations of 170 kg N ha $^{-1}$. This was independent of the feedstock type from which the digestate was produced. This behavioural effect can be translated into a habitat function, in that, over 80% of earthworms migrate away from the area (see section 1.3.1 iv for more on habitat function). When given a choice, the earthworms showed a species-specific avoidance/ preference to different treatments at concentrations of 220 kg N ha $^{-1}$ and above. This preference was lost when the treatment had been aged for one week prior to the trial. Mortality rates as a result of the laboratory conditions were also species-specific. These results may be considered in recommendations for farmers who are using digestate as a fertiliser and who aim to promote soil biodiversity in particular earthworm populations.

3.4.1 Effects of treatment due to organic matter and nitrogen concentration

The effects organic fertilisers have on earthworm populations have frequently been investigated (Cotton & Curry 1980, Edwards & Lofty 1982, Moreira *et al.* 2008). The nitrogen and the organic matter (OM) content of fertilisers are commonly linked with earthworm behavioural responses. OM causes earthworm attraction, while the effects of nitrogen are dependent on the concentration applied (Edwards & Lofty 1982, Moreira *et al.* 2008). Moreira *et al*. (2008), found earthworms were attracted to soil treated with digestate sewage and slurry at concentrations of around 61 kg N ha^{-1}. They also found a greater attraction when concentration of nitrogen increased from 59.3 kg N ha^{-1} to 118.6 kg N ha^{-1}. Edwards & Lofty (1982) found a correlation between the number of earthworms in field plots and an increase in nitrogen application (Edwards & Lofty 1982). Earthworms in the ABT's above were repelled from the treated soils into untreated soils at a concentration of 170 kg N ha^{-1}. The earthworms also demonstrated large weight losses when forced to inhabit soils of 170 kg N ha^{-1}. The results from the LD_{50} experiments for three, six and 14 days on *E. fetida* also all ranged between 170- 208 kg N ha^{-1}. These results together suggest that 170 kg N ha^{-1} is around the maximum concentration that earthworms can tolerate before the treatments have negative effect on behaviour and survival.

No effect was found on survival in either the slurry or digestate treatment at 21.25 kg N ha^{-1}. In addition, the highest numbers of *E. fetida* cocoons were produced at this concentration of digestate. As the typical concentration applied is around 21.25 kg N ha^{-1} (estimated as the permitted maximum nitrogen content averaged over four spreads per year), it would appear that current practice does not harm earthworms. As nitrogen concentrations increased, fewer *E. fetida* cocoons were found, with none found at concentrations of 220 kg N ha^{-1} or above. Neither of the species suffered a significant percentage mass decrease in the ABT's at the low (42.5 kg N ha-^{1}) or the medium (85 kg N ha $^{-1}$) test concentrations. Using digestate below 170 kg N ha^{-1} therefore appears to be relatively safe for both earthworm species, although exceeding these limits may cause problems.

Moreia *et al*. (2008) may have found earthworms were attracted at the high nitrogen concentrations used within their experiment due to the high OM content in their treatments (15% compared to 4% used in this chapter). As more material was spread to increase the N content, this also meant that more organic matter was also spread. The increased levels of organic matter therefore may be the main attractant for the earthworms (Moreira *et al.* 2008). This was not seen within the ABT's as when more treatment was applied, the earthworms displayed weight loss. Increased organic matter has been found to have beneficial effects on earthworms. Brauckmann and Broll (2007) found that earthworms fed on digestate for 10 weeks increased their mass by 16% while earthworms exposed to the liquid faction only, increased their mass by 10%. It has also been observed that earthworms were attracted to plots treated with farmyard manure up to a concentrations of 200 kg N ha^{-1} (Edwards & Lofty 1982). This suggests OM is an important feature for increasing earthworm biomass and may also be related to their behavioural responses.

Organic matter may provide some additional benefit than just attracting earthworms, (Moreira *et al*. 2008; Brauckmann & Broll, 2007; Edwards & Lofty 1982). For example, the it may act as a buffer towards harmful chemicals within the treatments, reducing the earthworms' exposure. This may especially be the case for chemicals that are pore-water mediated, such as those seen in metal uptake (Saxe *et al.* 2001). Exposure to such chemicals has the potential to react with the earthworms' mucus-covered epidermis, although more research into the mechanisms behind this is required (Van Gestel & Weeks 2004). Other research has shown that slurry used as a fertiliser at similar N concentrations to manures can have detrimental effects on earthworms (Curry 1976). From the experiments, high exposure to the treatments described in this chapter resulted in the mucus covering of the earthworms becoming dry and sticky and the earthworms to become covered in soil (personal observation). This therefore may be an indicator of earthworms in a state of stress.

3.4.2 Differences between the two earthworm species

The suitability of species may depend on the aim of the eco-toxicological work. For example, if the aim is to identify whether a chemical is harmful or not, recognised laboratory species may be the most suitable as extensive studies have already been conducted on them. However if the purpose of the research is to have ecological field significance, it may be better to use an ecologically relevant species, hence the two species studied here. As both species are also members of different ecological functional groups (see introduction section 1.3.1.1.ii), the results could also be used to consider community behavioural changes. During these trials, the two species *E. fetida* and *L. terrestris* responded differently, demonstrating the importance of using different species in eco-toxicological work.

i) Species preference towards treatments

Within this study, a species-dependent preference towards treatment was found. *E. fetida* preferred digestate to slurry, while *L. terrestris* preferred slurry to digestate. This preference was seen in multiple experiments conducted including the ABT's and the LD_{50} /LT_{50} experiments. Earthworms have shown a species preferences towards soil fungi, manures and other organic materials and animal manures (Neuhauser *et al.* 1980, Bonkowski *et al.* 2000, Loh *et al.* 2005). The concept of the different earthworm species having different preferences is not unusual.

Within the toxicity tests, *E. fetida* inhabiting soil with a digestate concentration of 280 kg N ha^{-1} and 340 kg N ha^{-1} required more time to reach their LT_{50}, compared to the *E. fetida* inhabiting soil treated with slurry at the same TKN concentrations. This suggests *E. fetida* has a better tolerance to digestate than slurry. Also, when given the choice between treatments during the ABT's, at concentrations of 170 kg N ha^{-1}, significantly more *E. fetida* individuals were found in the digestate treated side of the chamber, compared to the slurry treated side. Again this suggests a preference for digestate over slurry. This preference choice may have been expected due to *E. fetida's* ability to inhabit compost heaps, where high levels of ammonia are found (Amon *et al.* 2006). Although *E. fetida* may prefer digestate over slurry, they were not necessarily repelled by the slurry treatment, as there was no clear treatment preference seen within the ABT's at the lower concentrations.

The reverse was seen in *L. terrestris* as they took longer to reach the LT_{50} in soils treated with slurry at 280 kg N ha^{-1} and 340 kg N ha^{-1} compared with digestate at the same TKN concentration. This suggests they had a better tolerance to slurry than digestate. Also in the ABT's, significantly more *L. terrestris* were found in the slurry treated soil with 170 kg N ha^{-1}, than in the digestate treated soil at the same concentration. For *L. terrestris,* the preference for slurry over digestate may be due to a dislike of ammonia realised by the digestate. As the slurry contained more OM than digestate, there is a potential that less ammonia was given off during application, as by increasing OM within slurry less ammonia is lost (Amon *et al.* 2006, Novak & Fiorelli 2010). Also, an 18% increase in ammonia levels have been found in fields after the application of digested slurry compared with untreated slurry (Amon *et al.* 2006). Although *L. terrestris* are usually considered to be attracted to the matter within organic fertilisers (Edwards & Lofty 1982), in this case, the choice may also be due to a repulsion of the ammonia emitting digestate. This was seen within the ABT's where slurry treated soils were more populated than digestate treated soils for any concentration or age of treatment, although the difference in OM between the two sides of the chamber would have been minor.

ii) Species sensitivity

The species differed on their level of sensitivity to the two treatments. In other studies species dependent sensitivity has been identified in earthworms (Edwards & Brown 1982, Spurgeon & Weeks 1998). From our toxicity test results, *E. fetida* had a higher sensitivity to both treatments, requiring lower concentrations of each to reach its LD_{50} when compared with *L. terrestris*. There was 100% mortality seen at 220 kg N ha^{-1} in both digestate (LT_{50} 2.11 ± 0.18 days) and slurry (LT_{50} 1.73 ± 0.19 days) in *E. fetida*, while 100% mortality was not reached at any concentration with *L. terrestris*. As the *latter* were on average 12 times larger than the *E. fetida*, the potential concentration effects may have been due to individual size. By standardising the results to represent each species as a g^{-1} LW, a more accurate comparison could be made between the species. Here, *L. terrestris* was found to be the more sensitive species, requiring 4 times lower concentration of slurry and 5.5 times lower concentration of digestate to reach its LD_{50} compared with *E. fetida.* The differences between sensitivity may also be due to the differences in area to volume ratios. This therefore may have consequences on the survival of the juveniles of the two species, and may mean that smaller individuals are more likely to die, regardless of species.

L. terrestris appeared to be the hardier of the two species. The LT_{50} for *L. terrestris* at 220 kg N ha^{-1} of digestate was 35 ± 8 days and for slurry was 34 ± 8 days, both which exceed *E. fetida* whose LT_{50} was 2.1 ± 0.2 and 1.7 ± 0.2 days. For these trials, *L. terrestris* LT_{50} therefore both exceeded the experimental time of 14 days. This enabled the research to go on for longer and so more data points could be collected and could provide a more detailed description of the effect time after application has on the earthworms. In comparison, *E. fetida,* survived less than a week at the higher concentrations. In digestate, the survival rate continued to decrease after seven days with *L. terrestris*, whereas for *E. fetida*, all the individuals had died at and around 220 kg N ha^{-1}. This means *L. terrestris* can offer researchers an agriculturally relevant model species that can be used in the laboratory. They survived longer than *E. fetida* at higher concentrations and, when considering their mass, can be considered to be more sensitive as detailed above.

Edward and Brown (1982) found *L. terrestris* to be more sensitive to benomyl, a pesticide, than other species such as *L. festivus,* an epigeic species, similar to *E. fetida. L. terrestris* was also found to be more sensitive than *E. fetida* in other studies such as testing the effects of cadmium nitrate (Fitzpatrick *et al*. 1996) and other agricultural chemicals such as pesticides (Jones and Hart (1998). This pattern of better tolerance in *L. terrestris* at their usual body weight and higher sensitivity when mass is used to report the LD_{50} potentially makes *L. terrestris* a good species for experimental work.

3.4.3 The safe use of digestate

Currently, DEFRA recommends an average of 250 kg N ha^{-1} yr^{-1} as the maximum nitrogen that can be spread across the entire farm (DEFRA 2009d). For farms located in Nitrogen Vulnerable Zones (DEFRA 2011b) and organic holdings (Soil Association 2009a), the maximum average is 170 kg N ha^{-1} yr^{-1}. Although it is unlikely a farmer would spread all of their nitrogen allowance each year, there is a potential risk that they could spread more than 170 kg N ha^{-1} in fields used to grow nutrient demanding crops. In particular, farmers may grow maize, an energy hungry crop, to feed their anaerobic digester and therefore use the digestate to fertilise the field. As seen within the results from this chapter, applications above 170 kg N ha^{-1} could possibly have negative effects on earthworm populations. For organic farmers who rely on their earthworms to maintain soil fertility, disrupting the earthworm population may result in reduced crop yields (Mader *et al*. 2002). Farmers must therefore carefully consider how they apply their digestate to reduce this risk of negative effects on earthworms, while also achieving the nitrogen content they require for the crops. One method is to ensure the applied material has a high percentage organic matter content, however this will result in more material being spread and a greater energy expenditure in spreading (see chapter 5).

The age of the treatment from application had an effect on both species of earthworms' behaviour and their mass change. In the ABT's, mixing either treatment with soil one week prior to the introduction of earthworms resulted in a lower % mass change than earthworms introduced to freshly made soil treatments. A drop in weight can indicate earthworm stress or changes in feeding behaviour (Neuhauser *et al.* 1980, Van Gestel & Weeks 2004). As a result, mass change can be considered a sensitive indicator of ecological toxicity (Zhou & Liang 2003, Xiao *et al.* 2004). At the highest concentration (170 kg N ha^{-1}) in the ABT's, freshly mixed treatments caused a higher daily mortality for both species than in the ABT's using one week old treatment. This suggests some of the agents causing earthworm mortality and mass loss may be volatile and therefore their effects reduced after one week of air exposure.

Ageing of soil polluting contaminants has previously been found to reduce overall toxicity (Spurgeon & Weeks 1998, Van Gestel & Weeks 2004). As ammonia emissions are high for a few days after spreading, it is possible that ammonia loss through the ageing process makes both digestate and slurry more inhabitable for *L. terrestris* and *E. fetida*. After one week of spreading, the level of emissions from both digestate and slurry would be lower (Banks *et al.* 2011a). This would result in less ammonia within the immediate soil area that could potentially cause earthworm behavioural changes. Composting materials before application may reduce the amount of volatiles within the material and therefore reduce the earthworm's exposure during application. Composting also increases a materials OM%, which again has been shown to increase earthworms' attractiveness to digested materials (Moreira *et al*. 2008; Edward & Lofty 1982). The material used in Moreira *et al*. (2008) may already have been low in the volatile chemicals potentially responsible for the high avoidance found within our ABTs. Nitrogen form may therefore have an impact on earthworm behaviour and survival and should be monitored when used in the field.

In these experiments the digestate was mixed completely into the soil. This would be difficult to achieve in the field and would require high levels of soil disturbance. Over time, the earthworms would aid the mixing of the treatments into the soils, but this would not have been achieved within the length of these trials. The way that the digestate is incorporated may have different effects on different earthworm species. As the test epigeic earthworms live within compost-like environments, they may tolerate constant exposure to digestate like materials better than other species. Earthworms from other functional groups feed in different ways, for example, *L. terrestris* prefer to live in burrows and only come to the surface to feed and mate (Edwards & Lofty 1972). Their limited exposure to high levels of organic material applied to field surfaces may be a survival strategy. High levels of ammonia release have been recorded after the spread of digestate, management suggestions to reduce this include injection application of fertilisers (Schlamadinger *et al.* 2006). Farming methods that minimise the release of ammonia may reduce some of the negative effects digestate has on earthworm populations. On the other hand, the injected digestate may become trapped within the soil, which would increase the length of exposure for earthworms and other soil biota. Fertilisers are not the only source of stress acting on earthworm populations, tilling and ploughing fields can result in high earthworm mortality (Whalen *et al.* 1998, Pfiffner & Luka 2007) and a combination of these actions could damage numbers beyond recovery. It is therefore important not to consider the isolated effects fertilising may have on populations, but also consider the whole agricultural system when monitoring earthworm losses.

When assessing the suitability of a product, it is important to consider the rate of recovery of population numbers (Van Gestel & Weeks 2004). Earthworm populations with losses of up to 90% have been shown to recover within one year if the toxicity of the chemical lasts for less than 50 days (Jones & Hart 1998). Although recovery is possible, losses of 50% and over are considered unacceptable by the European Plant Protection Organization/ Council of Europe. Concentrations above 170kg N ha^{-1} showed a greater than 50%

mortality after less than a week in earthworms and therefore concentrations above this may potentially cause 50% mortality to earthworms in the field.

Currently advice on the use of digestate is available form WRAP in the PAS110 and the Quality Protocol (WRAP 2008). These do not consider the effects of soil biota through application of digestate, and are more concerned with reducing potential pathogen risks; environmental pollution and ensuring toxic metal limits are not exceeded. The work within this chapter therefore could be used to compliment recommendations on how best to use digestate so as to minimise its ecological impact.

3.4.4 Limitations within the research

This research would have benefited by being conducted at a field scale and over a longer time period. By basing the experiments in a setting more familiar to farmers, a greater understanding and acceptance of the findings might be obtained. Long-term studies conducted on agricultural products are recommended to fully understand short term and long term changes to the soil ecosystem (Chapter 2). Long-term studies should incorporate multiple species, including bacteria, fungi, invertebrates and plants to fully appreciate the effects products have on soil communities.

Environmental factors such as temperature were controlled for within the bioassays, which may lead to unnatural responses. Because organic farmers rely on a holistic ecological system to help generate viable crop yields, testing the direct effects of the product on target species may not be sufficient. Indirect effects felt within the intermedial soil community may also be of great importance to how earthworms respond and how soil fertility is affected. By excluding these effects, a full understanding of the results cannot be achieved and realistic predictions cannot be made. This can be overcome by including field based experiences when assessing the quality of a product.

As field trials cannot always provide the detail required for chemical and behavioural analysis (see chapter 2), it is clear that there is a need to modify the standard methodology set out by the ISO to better accommodate earthworm species like *L. terrestris.* These species can then offer scientists an ecologically relevant and sensitive model organism to work with (Mataalvarez *et al.* 1993, Van Gestel & Weeks 2004, Landrum *et al.* 2006, ISO 2008). For example, ISO recommend chambers of 6cm deep, which are too shallow for *L. terrestris* which can live at depths of up to three metres (Sims & Gerard 1985). Stress caused by such physical restrictions may cause abnormal behaviour. For instance increased light exposure may deter them from feeding, resulting in a decrease in mass, compounding the stress they are subjected to.

3.5 Conclusions

The findings within this chapter highlight a number of issues regarding the use of digestate as a fertiliser, and in using standardised earthworm bioassay methods for environmental risk assessment work.

- Earthworms show a habitat functional effect by avoiding areas of high contamination (170 kg N ha^{-1} maximum nitrogen spread limits within organic farming) of both slurry and digestate from a range of feedstock types.

- Physiological changes (weight changes) can be used as an indicator of sub-lethal conditions and were witnessed as both an effect from treatment and as an indicator of method suitability.

- A preference to treatment type was species dependent and evident in a number of trials with *L. terrestris* preferring slurry, and *E. fetida* preferring digestate.

- The ageing of the treatment in soil for one week reduced the habitat function effects on earthworm behaviours.

- *L. terrestris* had a higher tolerance to the treatments, and when standardised for live weight, had a higher sensitivity to treatments.

Chapter 4

A study of organic farmers' opinions about on-farm anaerobic digesters

4.1 Introduction

In response to the current international political drive to increase the use of renewable energies to 20% by 2020, (EC 2009) the UK government, as part of their Renewable Energy Directive, has pledged to source 15% of the UKs energy from renewables (DECC 2009c). To achieve this, the UK government is offering financial incentives for those generating and using renewable energy under the Renewable Obligation Order (DECC 2009b, DECC 2009c). These incentives are available for many renewable energy enterprises including hydro, biomass, wind and solar power. Participants are paid even when the energy generated is used on-site rather than sold to the National Grid. Farmers and land owners have access to land benefitting from a range of natural resources including; wind, sun and water. These resources can be utilised to generate renewable energy, and as a consequence, contribute towards achieving government renewable energy targets. Some renewable systems also have the potential to improve other agricultural practices (Seadi & Lukehurst 2012). In particular, anaerobic digesters can provide a farmer with renewable energy in the form of biogas and also have the potential to promote good agricultural practice by improving waste and nutrient management methods, and reducing air and water pollution (Yiridoe *et al.* 2009).

The uptake of anaerobic digesters has been successful in some European countries, for example, Germany. This success has been reported to be linked with the direct subsidies available to farmers and lenient policies regarding waste (Weiland 2000, Banks *et al.* 2007, Weiland 2010). In contrast to this, countries where financial incentives were slow to be provided, such as Finland, the uptake of anaerobic digesters has been much slower (Banks *et al.* 2007). Currently, there are around 33 on-farm anaerobic digesters in the UK (NNFCC 2011) despite the availability of financial incentives, such as Feed in Tariffs (FIT's) and Renewable Obligation Certificates (ROC's) (Banks *et al.* 2007, Lantz *et al.* 2007, DECC 2011b). It may be possible to identify the reasons for slow uptake by gaining a better understanding of UK farmer behaviours and motivations towards new enterprises.

Although financial motivations cannot be ignored when considering the reasons behind why a farmer chooses to adopt a new technology on their farm (Banks *et al.* 2007, CEC 2007, DECC 2011b), financial incentives are often not the best method with which to encourage the long-term establishment of a new technology. Reliance on such methods may result in the farmer reverting back to their previous operations when financial incentives are withdrawn from schemes, (Rigby *et al*. 2001). The incentive to make a major change on a farm must be a result of more than financial reasons if the change is going to remain after financial incentives are withdrawn, unless the change is financially viable on its own, or has worthwhile lasting incentives.

A farmer's decision on whether or not to participate in an agricultural scheme is influenced by both personal variables, i.e., the farmer's own attitude toward the scheme; and social variables, i.e., how the farmer perceives social pressures acting upon them and their willingness to comply (Gorton *et al.* 2008). A personal variable, for example, may be the farmer's lack of motivation to participate, even if there is no financial cost to them. This may be particularly relevant if they have previously considered schemes that have followed inconsistent policy goals (Willock *et al.* 1999, Ilbery & Saxena 2009), or that require a lot of paperwork to be completed. This has been shown to increase farmers' stress levels (Schulman & Armstrong 1989). Farmers generally avoid schemes requiring long-term commitments as they lose the flexibility to be able to react to the commercial market. Such schemes may affect the re-sale of their land; and if the farmer decides to leave the scheme before the end-date, they may be required to pay back any subsidies (Ozores-Hampton 2000). Therefore to have lasting changes on a farmer's behaviour, the farmer must believe that the action promoted by the policy will have considerable beneficial effects. It is therefore only through a change in behaviour that long-term policies are successful (Ozores-Hampton 2000, Rigby *et al.* 2001, Darnhofer *et al.* 2005). In addition to financial issues, the current low uptake of anaerobic digesters may therefore be due to farmers having a lack of confidence in current policy, a lack of personal belief that anaerobic digesters will actually work for their farm and a perception that adoption of such technology will require considerable effort (Hobbs *et al.* 1999, DECC 2011b).

In order to alter a farmer's perception of anaerobic digesters from being just a money making opportunity, anaerobic digesters should also be promoted through the co-benefits they offer. For example, their ability to recycle waste, to reduce pollution and to create renewable energy that can be used onsite (Sheppard *et al.* 1992, Walker *et al.* 2009, Yiridoe *et al.* 2009). Given the ethos of the organic movement, it could be expected that many organic farmers would be particularly interested in such co-benefits, and as a result, organic farmers may be a good group to encourage to invest in anaerobic digestion technology (Bailey *et al.* 2008). There are financial risks involved with converting to organic farming, and as a result conversion could be considered a challenge (Darnhofer *et al.* 2005). Two main forms of organic farmers currently exist, the committed and the pragmatic (Fairweather 1999). The committed organic farmers are those who usually convert for environmental and ethical reasons, rather than financial rewards. They are often considered to be the older generation of organic farmers, being organic pioneers. Their beliefs often stem from a fear of chemicals on foods, dislike of pollution, and a respect for natural processes (Balfour 1943, Myers 2006). Although pragmatic farmers also have environmental concerns, they are likely to have adopted organic farming to exploit a niche within the market and receive financial incentives. They have typically converted to organic farming more recently than the committed organic farmers. Both types of organic farmers can be considered as entrepreneurs, due to their risk taking and lack of fear of novel farming techniques (Padel 2001), which further suggests that they may be a good group to target to promote the establishment of anaerobic digestion technology (Schoon & Te Grotenhuis 2000, Lantz *et al.* 2007). On average, organic farmers are younger than conventional farmers, with a higher level of education (Padel 2001) and therefore may be more likely to gain from long-term commitments to an anaerobic digester, and more likely to understand the technological side of anaerobic digesters and the training required (Padel 2001, Rigby *et al.* 2001, Soil Association 2009b). It is because of this, and the other co-benefits discussed, that anaerobic digestion technology may be well suited to organic farming, regardless of the reason for the farmer converting to organic farming in the first place (Lantz *et al.* 2007).

Due to the strict certifying practices organic farmers follow to obtain their organic status, they may face different or additional barriers towards adopting an anaerobic digester compared with conventional farmers. Complications such as the farmer's requirements to manage fields in rotation, and to use preventative methods rather than reactive methods to deal with pests and improve soil fertility, make decision making less flexible (Lampkin *et al.* 2008). Because organic farmers may be interested in the co-benefits associated with anaerobic digesters, the government and organic certifying bodies need to identify the barriers associated with organic farms investing in anaerobic digesters and provide methods to overcome them.

In an attempt to overcome other potential barriers towards the adoption of an anaerobic digester (Rigby *et al*. 2001) DEFRA have formed the Anaerobic Digestion Task Group (DEFRA 2009b). Through this group, DEFRA aim to increase the awareness of anaerobic digesters by offering farmers the opportunity to attend conferences and seminars, including anaerobic digester demonstration plants that are funded by the Waste and Resources Action Programme (WRAP). WRAP have also created the PAS110 to provide farmers with guidance on using digestate (WRAP 2008). By identifying which barriers farmers perceive to be the most significant and what their general thoughts are about anaerobic digesters, alternative methods to either educate or support farmers through their decision making and adoption process can be created.

Using questionnaires and interviews, the aim of this chapter is to establish the opinions that organic farmers have towards anaerobic digesters, with the purpose of trying to identify the barriers that currently exist against their adoption and to identify the farming groups that are most interested in the technology. To achieve this, the objectives of the chapter are:

1. To investigate to what extent organic farmers consider anaerobic digesters to be a suitable enterprise for organic farming. This will be done by:

i) Examining whether organic and conventional farmers show differences in the level of importance they assign to combating environmental issues.

ii) Assessing how well anaerobic digesters fit within the ethos of organic farming and the standards within which they must operate.

2. To identify what the barriers are towards adopting an anaerobic digester, and whether these differ for organic farmers compared with conventional farmers. This will be done by:
    i) Comparing the results from a questionnaire to conventional and organic farmers on how they rate the importance of a list of barriers.
    ii) Investigating the reasons behind the answers provided by the organic farmers for the “ranking of barriers” question in the questionnaire. This will be done through interviews and will in particular examine the responses that were rated significantly different from the conventional farmers’ responses.

iii) Identifying other barriers not included in the questionnaire, and exploring why these may create farmers issues when investing in anaerobic digesters.

3. To create a profile of the type of farmers that are more likely, and less likely, to consider investing in an anaerobic digester. This will be done by:
   i) Identifying correlations between demographics collected in the questionnaires, and those farmers whom are likely to adopt anaerobic digesters.
   ii) Interviewing farmers to discover where they consider anaerobic digesters to be best suited and most feasible.

4. To identify areas where improvements need to be made to enhance the market for anaerobic digestion within organic farming. This will be done by;
   i) Identifying and evaluating the sources of information used by farmers.
   ii) Integrating and interpreting the results of both the questionnaires and interviews.

4.2 Methods

4.2.1 Data collection

Two techniques of data collection were used within this chapter; questionnaires and interviews. The questionnaires were used to collect a large sample of farmer opinions and perceptions of anaerobic digesters. Questionnaires are cheap, easy to analyse and avoid possible bias answers, which may occur when using interviews (Oppenheim 1992a). Data collected from questionnaires can be used to describe the sample and identify relationships between pairs of traits. However when correlations are found, these do not necessarily mean causal links, but allow predictions to be made on future samples (Oppenheim 1992a). Interviews were used to probe individual opinions and experience in greater depth than can achieved by questionnaires (Oppenheim, 1992a). The interviews could also be structured, according to the participant’s knowledge, to make the questions more relevant and reactive to topics of particular interest, while still creating complimentary data. By using these multiple methods in one chapter, both a breadth and the depth of information could be collected. Furthermore, using two methods can help isolate contradictions between two data sets (Oliver *et al.* 2012).

4.2.2 Questionnaires

Two questionnaires were used within this chapter. The first was designed, and the data collected by the University of Reading (Appendix 1). Here, 2000 farmers in England were questioned to investigate the general opinions of farmers towards anaerobic digesters. Contacts were obtained from the Yellow Pages business directory. The data from this questionnaire were shared, saving time and money, although the aims of the University of Reading’s analysis (Tranter *et al.* 2011) and this chapter are independent. The number of responses from organic farmers received from the first questionnaire was too low for robust statistics and to identify any characteristic patterns (Table 4.1). To increase the sample size, a second questionnaire was sent out to 450 organic farmers, whose details were obtained from the Soil Association’s certification list for the South West of England (Appendix 2). This list was used because it provided addresses of organic farmers only, and as a result increased the total number of organic responses, enabling a more meaningful comparison between organic and conventional farmer responses. South West organic farmers were chosen due to the high level of agriculture occurring in the region

(20.2% of total UK agricultural land) and because the area has a high proportion of the England's organic producers (45.9% - see figure 4.1) (DEFRA 2008b).

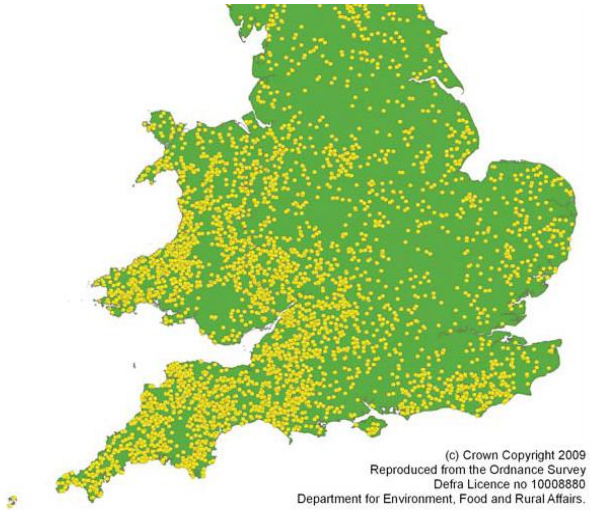


Figure 4.1. Distribution of organic farms within England and Wales (yellow dots). High densities of organic farms were found in the SW England and wales. Taken from (DEFRA 2009a).

Both questionnaires contained the same questions used for the analysis within this chapter, with one additional question on the second questionnaire. By using the same questions, potential ambiguity from rewording questions was avoided and allowed the data sets to be pooled. An explanation of anaerobic digestion and anaerobic digesters was provided in both questionnaires due to the potential problem that farmers may have had low awareness of the technology as a result of its current rarity.

i) Structure of the questionnaires

A variety of different types of questions were used to attempt to gain the most usable information from the participants. Question types included; questions requiring numerical values, some tick boxes between yes/ no and yes/ no/ maybe, scale ratings between 1 - 4, and an open ended question. Participants are more likely to complete questions if the answering technique is quick and does not involve much writing (Oppenheim 1992a). Therefore, an open ended question was used on only one occasion. There were two main sections to the questionnaire, with each section set out using a funnel approach (Lydeard 1991). General questions about the farm were asked first, and questions more specific to anaerobic digesters asked later (Oppenheim 1992a).

Data were collected on the farm and farmer regarding: farm size; land use within this area; main enterprise type; organic status; and how much of the farm was located in a Nitrogen Vulnerable Zone (NVZ), farmer's age and whether the farmer had any agricultural education. This was used to categorise the responders, and enabled a likely adopter farmer "type" to be created.

The anaerobic digestion technology section asked whether the farmers had any previous experience of anaerobic digesters, their likelihood of investing in an anaerobic digester in the next five years, and about potential perceived benefits and barriers of anaerobic digestion technology. To identify what would be the main benefits of using an anaerobic digester on a farm, three potential benefits were identified by the researchers. The participants were asked to rate each on its level of importance when considering adopting an anaerobic digester for their farm on a scale from 1 - 4 (1 = very important, 4 = of no importance). To assess the perceived barriers against adopting an anaerobic digester, a list of potential barriers was brainstormed by the research team from their previous experience in agricultural studies. The participants were then asked to rate the level of importance of each individual factor in this list as a potential barrier towards adoption on a scale from 1 - 4 (1 = very important, 4 = of no importance).

An additional question was included in the second questionnaire asking where the farmer had learnt about anaerobic digesters. This was an open ended question, aiming to identify key information sources. After the data were collected, the responses were coded into nine categories. These were:

1) The Press: including all agricultural and non-agricultural news sources. Examples include; "Farmers Weekly", "the television", "articles in the press".

2) "The Archers": a daily BBC Radio 4 series which in 2008 featured an anaerobic digester in the storyline.

3) Word of mouth: including "talking to people", and when people's names were given.

4) Local sites: knowledge of local anaerobic digesters.

5) Academic sources: Information gained from college or school.

6) Conferences: conferences, meetings and seminars.

7) Site visits: organised site visits to an anaerobic digester.

8) Organisational literature/ sources: where the farmer had approached a government department, NGO, or a company requesting information on anaerobic digesters. Some of these requests for information may have been accessed using the internet. To enable comparisons to be made, if they only listed the organisation, then it is categorised here.

9) Internet: Although this cannot identify which type of internet site was visited, it does show that farmers were actively searching for information on anaerobic digestion.

Farmers were also invited to participate in future research about anaerobic digesters. Their details were volunteered on the final page of the questionnaire. Volunteers were later contacted and used as interviewees.

ii) Data analysis

Data collected were entered into an Excel spread sheet and analysed using SPSS v.17. (SPSS, IMB corporation, NY., USA). Where suitable numbers of responses were achieved, contingency tables were used to analyse between questions with two or more options, for example, yes/ no responses, or questions that required the farmer to provide a level of importance on a rating scale (1 - 4). Yates' correction (*Fowler et al*. 1998) was applied to data sets with only one degree of freedom. Numerical variables, such as the farmers' age, the farm size, and number of livestock, were tested for normality and if not normally distributed were log transformed. Each variable was then analysed using a one-way ANOVA in SPSS v.17.

4.2.3 Interviews

Interviewing is defined as *"a conversation with a purpose. Specifically, the purpose is to gather information*" (Berg 2007) and are particularly useful for gaining an understanding of the perceptions of the participant. There exist three main interview structures, although they can be known by numerous names. These are; the standardised interview (formal or structured), the semi-standardised interview (semi-guided or focused), and the un-standardised interview (informal or nondirective) (Keats 2000). The differences between each are down to the degree of flexibility within their structure. Standardised interviews are often used by those who know what they want to uncover, asking set, and word-for-word questions to each participant. This makes the data highly comparable between subjects, but allows for no clarification or additional questions to be asked (Berg 2007). This format is not too dissimilar to the approach achieved through using questionnaires. Un-standardised interviews are the opposite, with no set order or wording of questions. They operate with different assumptions to those required for standardised interviews, with the questions being developed during the interview process. The semi-standardised interview is an intermediate between the two; with re-wording and re-ordering of a structured interview where seen appropriate. This allows the interview to probe into certain areas, while also covering the general topics allowing the data to be comparable with questionnaire data (Section 4.2.2.2).

i) Recruiting participants

The farmers who wished to be involved in interviews were contacted in early 2010. Some participants responded to the invitation to participate but said that they did not know anything about anaerobic digesters, and therefore felt that they would not be good candidates for the interview study. They were still encouraged to participate if they wanted to, and informed that the interview would not solely be about how much they knew, but also about their behaviour and opinions, as an organic farmer, towards renewable technologies (Keats 2000). As such, their “lack of knowledge” could therefore highlight other important issues. Furthermore, the exclusion of farmers that had no interest or little knowledge of anaerobic digesters could have resulted in the research sample being biased.

In total, seven interviews were completed within the period assigned for interviews. Ten interviews were planned, which would have been an optimal number, however three could not be completed and no additional interviews could be organised within the allotted time frame for interview data collection. Although more interviews would have resulted in more data, the purpose of the interviews was not to achieve a representative response from all organic farmers, but to expand on certain topics of interest. Low sample size therefore was not of critical importance for this study. Two interviews were held with two participants. This was due to a shared interest by both interviewees. As they shared many of the answers, or answers resulted in some discussion between the interviewees, they were not treated as individual interviews.

The participants were recruited through self-selection in response to the questionnaire; therefore there was a risk that the interviewees would be farmers who held strong opinions towards anaerobic digesters (either positive or negative). This was not considered a major problem as those farmers with strong opinions would be more likely to provide specific examples or emphasis on topic areas or issues not yet considered.

A cover letter containing details of the project was included in the initial contact. Researchers have commented on the importance of informing the interviewee of the value of the research (Keats 2000) and so this information was also reiterated prior the start of each interview, with the opportunity for the farmer to ask questions in person.

ii) Design of the interview

To enable a comparison of the responses of different subjects, a semi-structured interview was used (Gillham 2005). Four main topics were discussed in all the interviews; the aim of splitting the interviews into these topics was to prevent the interview feeling like an interrogation (Oliver *et al.* 2012). The four topics were used to create four main nodes for data analysis. The sample of farmers used for this study came from a range of backgrounds and farm types; therefore it was possible to probe further into certain subjects depending on the farmers' responses, utilizing the flexibility of the semi-structured interview (Appendix 3).

The four main topic areas discussed were:

i. The farmers' reasons for why they farm organically, and their opinions regarding pollution and waste on farms (questions 1 - 5).

ii. The farmers' knowledge, experience and opinion of anaerobic digesters in the context of organic farms (questions 6 - 8).

iii. The farmers’ opinions and knowledge on other renewable energy technologies on farms (question 9 - 10).

iv. Any additional comments (questions 11 - 12).

To ease the interviewer and interviewee into the process, simple questions were asked at the start to enable both to gain the confidence to talk openly in front of the Dictaphone (Wengraf 2001). These four topics were used to address the four objectives of the chapter:

1. ***To investigate to what extent organic farmers consider anaerobic digestion to be a suitable enterprise for organic farming.***

Data from topic one was used to address this aim. It explored what the motivations were behind the farmers’ initial decision to become organic. It also investigated whether the organic farming practices they use would affect their flexibility in adopting a new technology, such as an anaerobic digester. The primary benefits of anaerobic digesters are their ability to deal with waste and reduce pollution; therefore these areas of organic farming were explored in detail with each farmer, with the intention of seeing how important these issues were to the farmer in influencing them to convert to organic farming.

2. ***To identify what the barriers are towards adopting and anaerobic digester, and whether these differ for organic farmers compared with conventional farmer.***

Data from both topic two and three were used to address this aim. Topic two identified what the organic farmers know about anaerobic digesters, and enabled the participants to be categorised according to their levels of their knowledge. Only three compulsory questions were asked regarding anaerobic digestion technology for topic two. From these responses, tailored questions to best suit the farmer’s current knowledge of anaerobic digesters were used to gain the most useful information from the interviews. Reasons for a lack of knowledge and interest in the technology were identified and then were compared to their organic opinions from topic one above.

Topic three was also used to address this aim by identifying whether the farmers had considered any other forms of renewable energy technology, or whether renewable energy was even an organic concern. These responses were then used to see if the farmers had similar opinions towards potential barriers associated with investing in other forms of renewable energy technologies, or whether the barriers were only associated with anaerobic digesters.

3. ***To create a profile of the type of farmers that are more likely, and less likely, to consider investing in an anaerobic digester.***

Information to address this aim came from data collected on all topics. The farmers' responses were used to investigate whether renewable energy generation was suited to organic farming, in terms of the ethos and the practicality of organic farming, and if not why not. Their responses were then used to identify what characteristics are most commonly displayed by a farmer that is considering renewable energy generation and more specifically anaerobic digesters. Finally, their responses were used to consider whether alternative locations would be better suited for anaerobic digesters.

4. ***To identify areas where improvements need to be made to enhance the anaerobic digestion market within organic farming- In particular, access to information.***

Information to address this aim was taken from all the topics, in order to identify areas where improvements could be made to increase the uptake of anaerobic digesters. Opinions were derived from both the participants' responses and from the thoughts of the researcher. This information was used to investigate what currently has been done to promote anaerobic digesters, the impact of this upon farmers, and to discover areas for further improvement.

Access to information was highlighted from the questionnaires as a potential factor that may affect farmer behaviours. Here it was explored in what way, and in what form, information is accessed, and which information is most trusted and most useful for farmers. This also enabled the lack of information to be discussed as a barrier for farmers adopting anaerobic digesters, and how this could be improved.

iii) Preliminary Interview

A preliminary interview with two participants was conducted prior to the main interviewing stage. From this, a number of changes were made to the order of the questions, and some of the questions themselves were re-worded to make them easier to understand, less ambiguous, and flow better. In the preliminary interviews one of the participants was knowledgeable about anaerobic digesters and another knew very little and therefore felt he could not respond to certain questions. This highlighted the importance of having two levels of anaerobic digester-related questions, and also having the flexibility to alter questions according to the interviewee's knowledge.

It was decided that the interviewees should be allowed to ask questions regarding the technology during the interview to enable them to express personal impressions of the technology in later questions. As part of the analysis of the interviews farmers were categorised on their level of knowledge of anaerobic digesters, gaining knowledge throughout the interview did not change the category to which they were assigned (see section 4.3.2 for details on knowledge level categories.)

iv) Interview analysis

Interview transcription was standardised across all interviews, with the entire document transcribed to reduce researcher selectivity of the text (Oppenheim 1992b). All interviews were transcribed by the researcher. Transcription is a form of translation (Gillham 2005), although transcription can be as simple as a script, it can lose many dimensions of speech such as emphasis, hesitation, pace, sarcasm and tone which may alter the meaning behind the words. Scripting how the words were said may therefore be important for certain issues (Gillham 2005). Therefore, notes were made where necessary. Appropriate punctuation was also ignored, unless it was clear and required to remove ambiguity from the interviewee's response (Truss 2003, Gillham 2005). After the initial transcription, each interview was re-listened to, and corrections made where necessary to the scripts. Paper copies were then sent to each participant, with the option to withdraw all or parts from the study, or question any part of the script for clarity. Participants were not given the option to make changes.

The final copies of each transcript were imported into NVivo9 package software (QSR NVivo version 9 ©, International Pty Ltd) so that relations and grouping of important quotes could be made. This enabled the data to be organised in the most efficient way. Topic headings within NVivo were decided upon to best answer the aims of the chapter. Relevant quotes from each interview were then searched through manually and grouped accordingly. Patterns between interviewee responses were identified using word frequency and word count functions. Highly used words were identified and considered to highlight the key issues of the interviews, and used to structure the main themes for discussion.

4.3 Results

4.3.1 Questionnaires

i) Responses

Questionnaire 1 had a response rate of 19%, with 381 of the 2000 questionnaires returned with two reminders sent. For questionnaire 2, a response rate of 28% was achieved, with 118 of the 450 questionnaires returned with no reminders sent. In total, 487 farms were regarded as either having 100% of their land certified as organic (organic) or 0% of their land certified as organic (conventional). This was self-defined by the farmer in question 7. Those farmers self-rating the total area of their farms between 99% and 1% organically certified were removed from the analysis. This was in total 21 farmers whose organic status ranged between 5% and 95% organic. This enabled only completely organic farmers and systems to be compared against conventional farmers. This led to a response rate of suitable questionnaires for analysis of 19% for the first questionnaire, and 26% for the second questionnaire. Data from both questionnaires were pooled to give 351 conventional farmer responses, and 136 organic farmer responses (Table 4.1).

Table 4.1. Total number of received responses and suitable responses for analysis between conventional and organic farms from two questionnaires. Organic farms not considered 100% organic were removed from analysis due to the large range of organic status (from 1% - 99% land certified as organic).

	Total sent	Total received	Response rate	Total usable	Conventional responses	Organic responses
Questionnaire 1	2000	381	19%	369	351	18
Questionnaire 2	450	127	26%	118	0	118
Total	**2450**	**508**	**21%**	**487**	**351**	**136**

As the initial farming sample used in questionnaire 1 was randomly generated, it was unknown what types of farms were included on the list. As only larger farms are likely to be included on business directories, larger farms may have been biased towards being sent questionnaires over smaller farms (Burton & Wilson 1999). It was therefore unclear whether the responses from each farmer should be considered in terms of their farm size, or as each individual farm i.e. the number of producers.

ii) Demographics of respondents

Details of the demographics of the respondents are below (Table 4.2). No differences were found between organic and conventional farmers' age, whether they attended formal agricultural education, or whether they had a slurry problem. Education levels between the organic and conventional farmers were not found to be significantly different. The average size of farm holdings in England is 54 ha, while for organic farms, the average size is 111 ha, and for organic farms in the SW England is 110.3 ha. This suggests the organic sampling was representative of organic farming sizes, while the conventional farming sample included either a high number of large, or very few small farms.

Table 4.2. A description of the demographics for the respondents from both questionnaires. Respondents are pooled according to organic status and tested for differences between organic and conventional (AD= anaerobic digester, ± S.E). NVZ*= Nitrogen Vulnerable Zone (DEFRA 2008a).

Demographic	Organic	Conventional	Sig difference
Farm size (ha)	102 ± 11	279 ± 19	F_{231} = -8.15 ***
Land in NVZ* (ha)	127 ± 17	308 ± 28	T_{261} = 2.49 *
Farms within a NVZ	50%	65%	χ^2_1 = 14.9 ***
Farmers age (yrs)	53.1 ± 0.9	54.7 ± 0.6	T_{245} = 1.45
Attended formal education (Y/N)	50%	59%	χ^2_1 = 2.92
Slurry problem (Y/N)	5%	9%	χ^2_1 = 1.17
Likelihood of adopting AD in 5 years (Y/N)	26%	39%	χ^2_1 = 5.17 **
Previously considered an AD (Y/N)	16%	11%	χ^2_1 = 1.54

As the geographical areas were different for the sampled farms, a direct comparison between frequencies of farm types could not be made between the organic and conventional systems. The farm type data are therefore used within the analysis as a demographic by which to compare opinions. Farm categorises were defined using the revised EC classification using Standard Outputs (SO). Details of the spread of farm types used within this analysis are detailed below in figure 4.2 and 4.3.

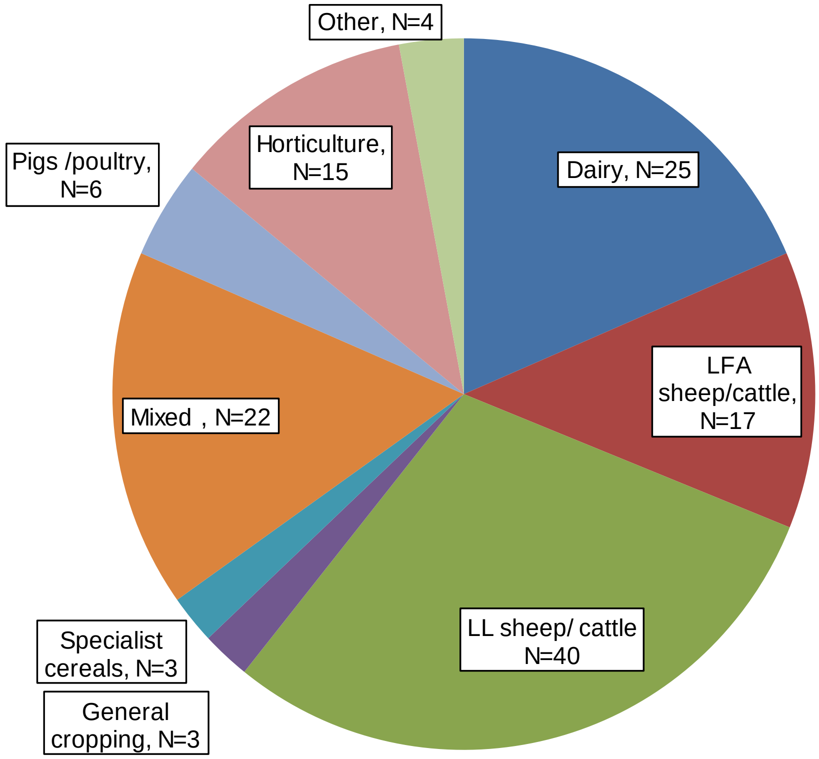


Figure 4.2. The range of enterprises found on the organic farms used within this chapter (N = 136) recorded from the questionnaires. Farming definitions were defined using the EC Classification of farm types. One farm did not disclose their enterprise and so was withdrawn from the figure. The majority of farms were located in the south West, which explains the high numbers of cattle and sheep farming, and the low levels of arable farming. (LL= Low Land, LFA= Less Favoured Areas).

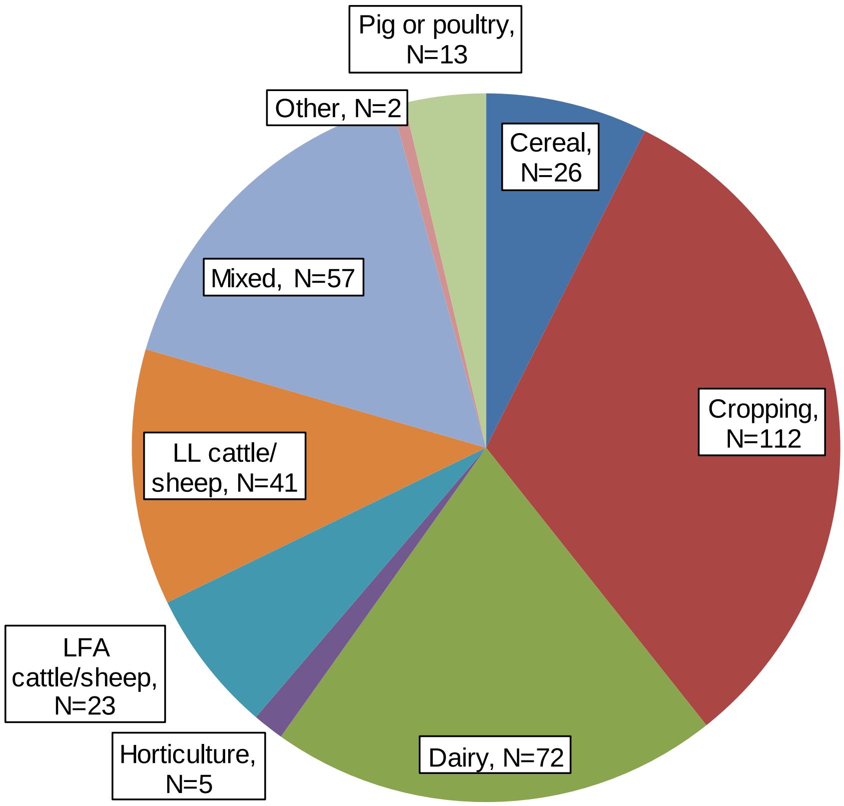


Figure 4.3. The range of farm types within the national conventional sample used for this chapter (N = 351). Farming definitions were defined using the EC Classification of farm types based on the data they provided regarding their farm size, land use and livestock numbers. (LL= Low Land, LFA= Less Favoured Areas).

iii) Predictors of whether a farmer was likely to consider adopting AD technology.

No relationship was found between the likelihood of an organic farmer to consider purchasing an anaerobic digester and: whether the farmer had an agricultural education (χ^2_1 = 0.001, P = 0.97), the farmer's age (T_{69} = 1.74, P = 0.086), the size of the farm (W_{127} = 2494, P = 0.21), or whether the farm was located on an NVZ (χ^2_1 = 0.001, P = 0.97). There was also no relationship between whether an organic farmer had previously considered an anaerobic digester and their likelihood of adopting one in the future (χ^2_1 = 1.72, P=0.19).

Conventional farmers with an agricultural education (χ^2_1 = 4.285, P <0.05) or that had previously considered anaerobic digester enterprises before (χ^2_1 = 28.125, P <0.001) were found to be more likely to adopt an anaerobic digester within the near future. There was a negative correlation between the likelihood that farmers would consider adopting an anaerobic digester and increasing farmer age ($F_{1,337}$ = 10.08, P <0.01), but a positive correlation between the likelihood of adoption and increasing farm size (F_{302} = -6.26, P <0.001).

Whether a conventional farmer would consider an anaerobic digester in the next 5 years differed significantly depending upon their farm enterprise (χ^2_8 = 20.45, P <0.01), whereas farm enterprise did not significantly affect the responses of organic farmers (χ^2_6 = 7.10, P = 0.311, general cropping and other were removed due to the low sample number). Of the conventional farms, dairy farms were the most likely to consider an anaerobic digester (55%), followed by cereal, and pigs or poultry farmers (both 46%). The least likely were the LFA cattle and sheep farmers. Of the organic farmers surveyed 33% of the pig and poultry farmers, and 33% of the specialist cereal farmers said they would consider an anaerobic digester in the next 5 years although the number for each of these farm types was low (total sample number was 6 and 3 respectfully). After these, dairy farmers were the most likely to say they would consider anaerobic digestion, with 7 of the 25 (28%) showing an interest in anaerobic digesters

Conventional farmers with larger herds were more likely to consider adopting an anaerobic digester (T_{75} = 3.37, P <0.001). Farmers with over 130 head of dairy cattle were more likely to consider adopting than those below 130 (χ^2_1 = 9.334, P <0.01). The number of dairy cattle an organic farmer had did not influence the likelihood of investing in an anaerobic digester (T_{22} = 0.41, P = 0.683).

The response from organic farmers stating they had a slurry problem was too low to allow statistical analysis. This meant the responses for conventional and organic farmers were pooled. Dairy farms were more likely to have slurry problems than expected by chance (χ_2^1 = 9.02, P < 0.05). Those farmers with slurry problems, were more likely to consider an anaerobic digester than those without slurry issues (χ^2_1 = 4.65, P < 0.05). This supports the idea that dairy farms are more likely to consider an anaerobic digester than other farm types.

iv) Perceived benefits of adopting an anaerobic digester

Three key benefits of adopting an anaerobic digester were identified to see how important farmers rated them. These were: to make a financial profit for the farm, to reduce the amount of pollution and contamination from the farm, and to reduce the farm's carbon footprint (Figure 4.4).

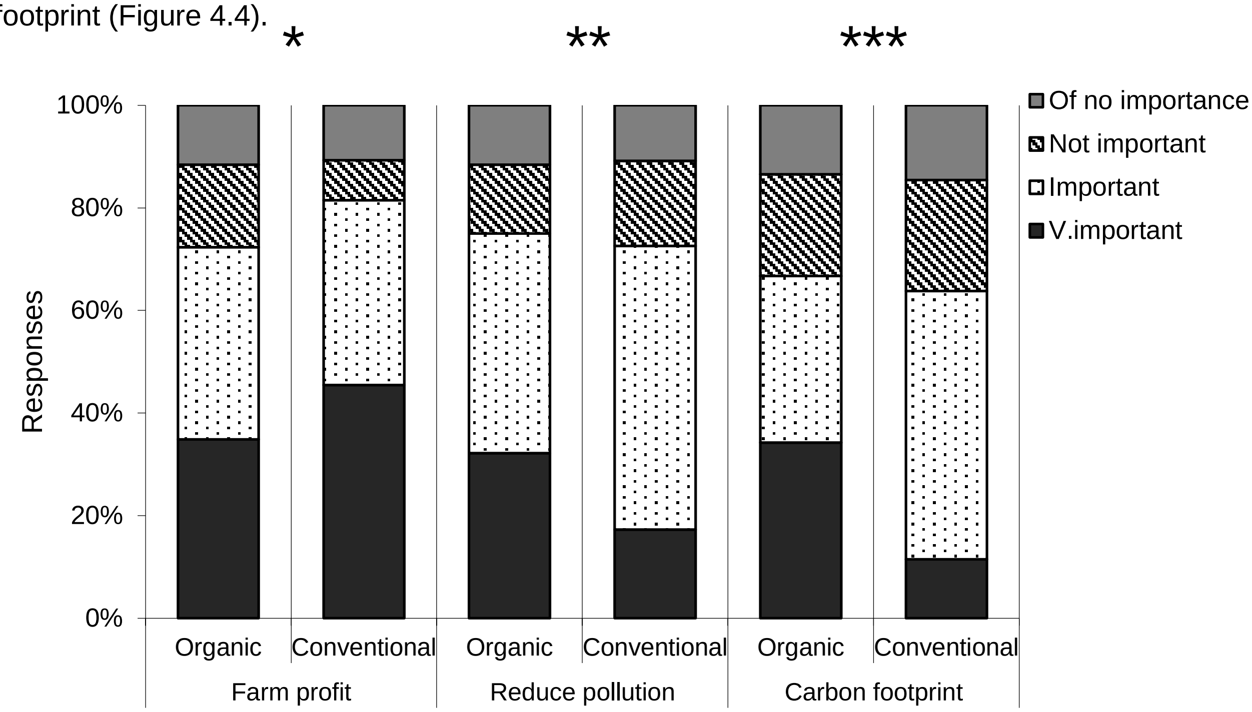


Figure 4.4. Responses from conventional and organic farmers rating the importance of benefits derived from using an anaerobic digester from very important to of no importance. Benefits of an anaerobic digester considered here were a) increasing a farm's profit (organic N = 112, conventional N = 297) (b) reducing the risk of pollution and potential contamination from waste management (organic N = 112, conventional N = 295), and c) reducing the carbon footprint of the farm (organic N = 111, conventional N = 287). Analysis between responses between the organic and conventional farmers were conducted using chi- squared (P <0.05*, P <0.01**, P <0.001***).

When considering adopting an anaerobic digester, maximising farm profits were most frequently rated as the most important benefit for both organic and conventional farms. However, in statistical comparisons between the importance of all three perceived benefits, organic farmers rated no one benefit as more important than another (χ^2_6 = 7.439, P = 0.28), whereas conventional farmers did rate the benefits as significantly different from one another (χ^2_6 = 112.43, P< 0.001). Therefore, this suggests that the benefits were all of similar importance to the organic farmers, whereas conventional farmers considered profits to be the most important benefit. Conventional farmers rated farm profits as a significantly more important benefit than organic farmers (χ^2_3 = 7.89, P <0.05). Organic farmers rated reducing pollution (χ^2_3= 11.36, P <0.01) and reducing their carbon footprint (χ^2_3 = 30.12, P <0.001) significantly more of a benefit than conventional farmers. Organic farmers rated reducing pollution and reducing the farm's carbon footprint with higher importance, compared with the rating given by conventional farmers.

v) Perceived barriers towards implementing an anaerobic digester

The barrier most frequently rated as "very important" for both organic (59%) and conventional (69%) farmers was the initial costs of establishing a digester (Figure 4.5). This was followed by the potential financial returns of the digesters being too low for conventional farmers (38%) and the disruption to the farmers' rotation for organic farmers (32%). The barrier with the highest frequency rating for "of no importance" was whether their tenancy agreement would permit it (Conventional = 65%, organic = 74%). The barrier with the lowest frequency of "very important" was the farmers' ability to learn how to run the digester.

Of the nine potential barriers listed, the responses from the organic farmers were significantly different for three of the barriers, compared with the responses given by the conventional farmers (Figure 4.5). Conventional farmers rate the potential low return generated from the anaerobic digester differently to organic farmers (χ^2_3 = 12.602, P <0.01), suggesting it is a more important barrier towards adopting an anaerobic digester, although both organic and conventional farmers rated low returns as an important barrier. Conventional farmers also rated the lack of information available differently to organic farmers (χ^2_3 = 9.124, P <0.05), rating it a more important barrier, compared with the organic farmers' responses. Farmers rated the potential disruption to the farms rotation system due to growing additional feedstock, differently (χ^2_3 = 9.221, P <0.05) with more organic farmers rating it a more important barrier to anaerobic digester adoption, compared to conventional farmers.

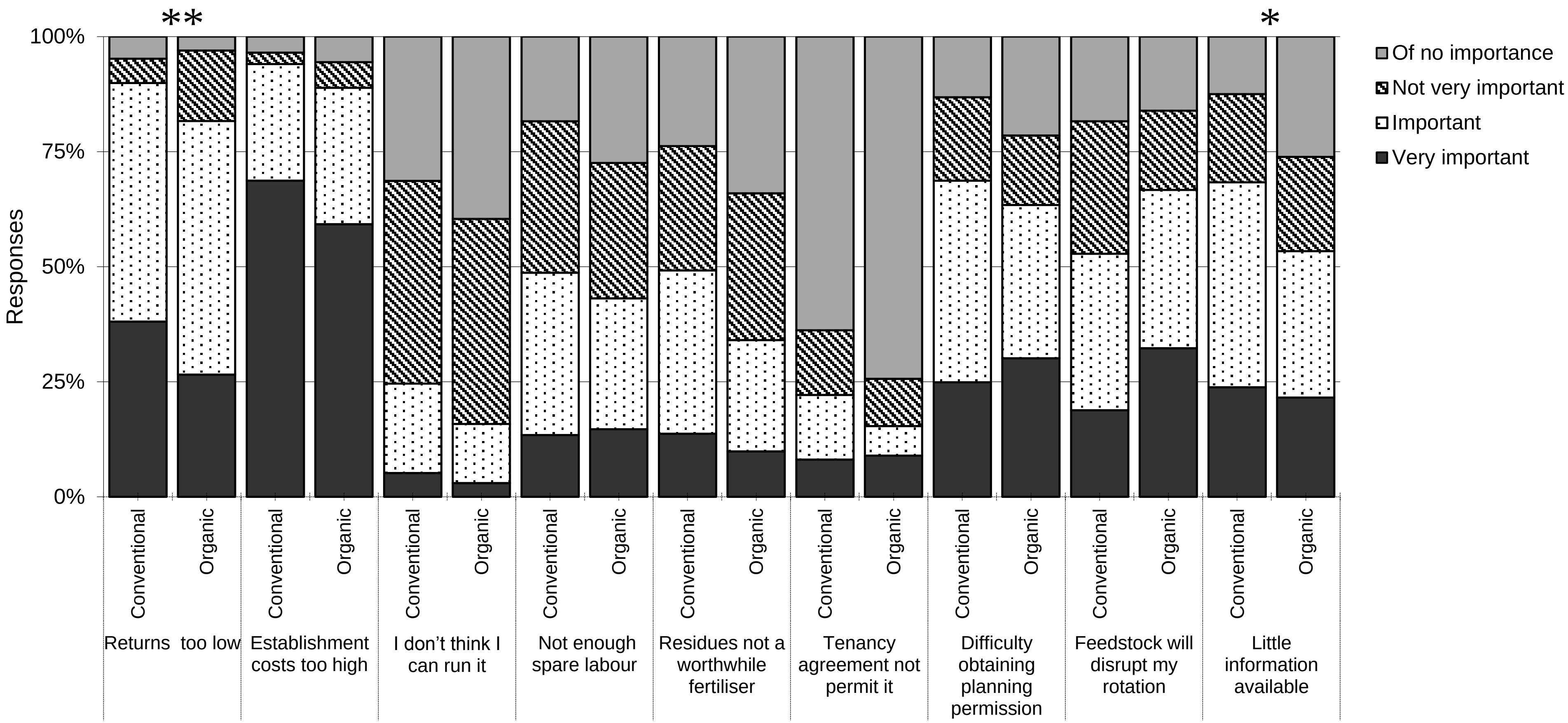


Figure 4.5. Rating of importance for nine potential barriers towards anaerobic digester adoption by organic and conventional farmers. Analysis performed was between the four levels of importance rated by the farmers compared between organic and conventional farm responses. (P <0.05*, P <0.01**)

vi) Sources of farmers' information on anaerobic digesters

In total, 58 respondents listed 85 sources of information used to learn about anaerobic digesters. These were pooled together to make nine main categories (Figure 4.6. See section 4.2.1.1 for details of how these categories were broken down). The counts for each source of information were too small to statistically analyse and were mainly collected for use within the construction of the interview questions (appendix 3). The most common source of information was from the press. The least common category was from academic sources.

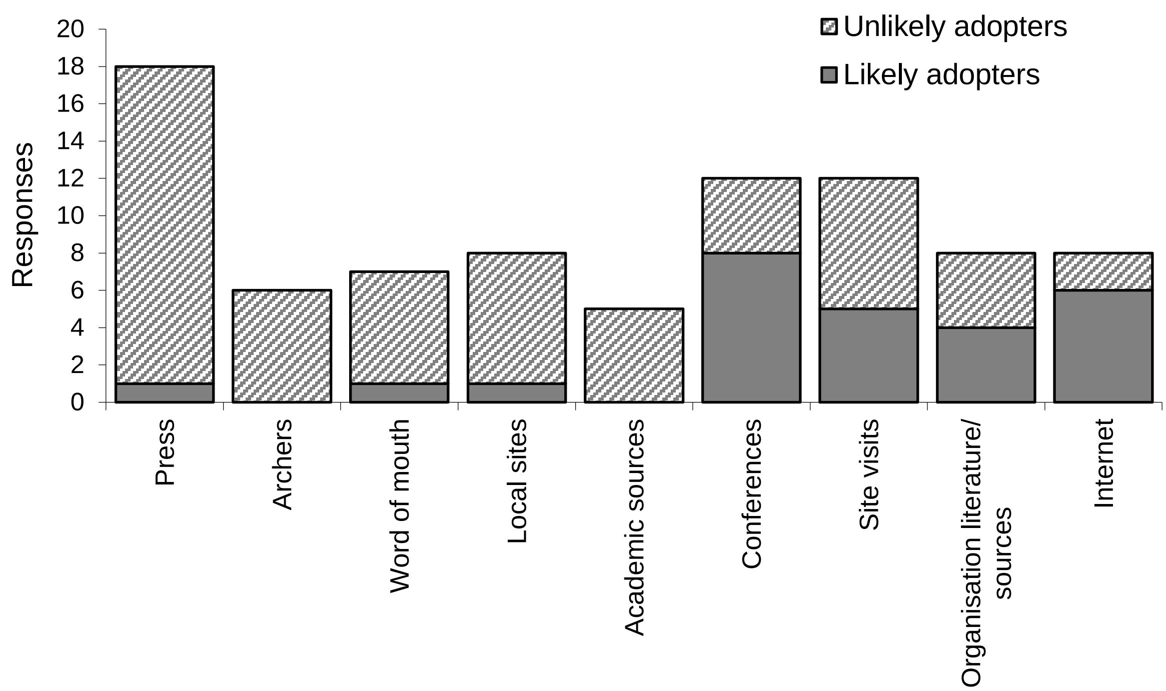


Figure 4.6. Response to an open-ended question regarding sources of information farmers have previously used to lean about anaerobic digesters (N = 85). Farmers were able to list as many different sources as they wanted, although many farmers did not answer this question at all.

Farmers that gained most of their knowledge about anaerobic digesters from sources such as "The Archers", the press, or from academic sources, were less likely to consider investing in anaerobic digestion in the near future. The farmers that would consider an anaerobic digester in the near future gained most of their anaerobic digester knowledge from attending conferences and site visits, or from internet searches and information from organisations such as ADAS, Institute of Grassland and Environmental Research (IGER), National Farmers Union (NFU) and Country Land and Business Association (CLA).

4.3.2 Interviews

Interviews took place between February and May 2009. In total nine organic farmers were interviewed in seven interviews, which lasted between 46 - 91 mins (average = 64 mins). Two interviews had two participants. In one of the double interviews, the farm manager (Interviewee B1) and farm owner (Interviewee B2) were present, whilst in the second, both partner owners were interviewed together (Interviewee A1 was the person who filled out the original questionnaire, and partner; Interviewee A2). For the double interviews, characteristics of the person who completed the original questionnaire were used for tables 4.3 and 4.4. Farmers ranged from 44 - 72 years old and came from a range of agricultural enterprises and farm sizes. All farms were located in Southern England and had organic certification from the Soil Association.

Table 4.3. Characteristics of the farmers interviewed. O/M□ is used for interview B as both manager and owner were present. Age and farm size have been categorised to increase the confidentiality for the participants.

Interviewee	A*	B*	C	D	E	F	G
Age (yrs)	50 - 59	41 – 49	50 - 59	60+	41 - 49	50 - 59	50 - 59
Farm size (ha)	<100	100 - 1000	100 - 1000	<100	1000+	<100	<100
Farm enterprises**	L,H	D,L	M	L	M	L	L,H
Organic type***	C	P	C	C	P	C	C
Manager or **O**wner	O/O	O/M□	O	O	M	O	O
Land NVZ (%)	0	70	100	100	100	0	0

***** Two interviewees present at interview
******Major enterprises practiced on the farm= **L**ivestock (excluding dairy), **H**orticulture, **D**airy, **M**ixed
*** Organic type **P**ragmatic or **C**ommitted. Defined using Fairweather's categorisations

To assess the participants' motivations for farming organically, they were categorised as either being pragmatic or committed organic farmers (Table 4.3). It is not always clear how to define organic farmers as one type or another; here Fairweather's definitions are used (see section 4.1 for more details). All the farmers interviewed showed concern for environmental issues, or were aiming to increase sustainability on the farm, but their motivations behind financial incentives differed (Fairweather 1999).

From the interview answers, a variety of information was collected regarding the farmers' opinions towards renewable energy and anaerobic digesters (Table 4.4). The level of knowledge the participants had about anaerobic digesters was categorised as either high or low. A high level of knowledge was assigned if they had looked into the systems practicality for their farm or if they had visited an anaerobic digester or attended conferences on anaerobic digestion technology. In addition, the farmer would have actively sought out information and knew technical details of the processes involved. A low level of knowledge was assigned if the farmers had only heard of anaerobic digesters and had a basic understanding of the process. These farmers had not sought out information themselves, but may have come across information from articles in the press, or had done basic searches on the internet on anaerobic digestion topics. All of the farmers had at least heard of anaerobic digesters and understood the basic system and process; this may primarily be due to the information included in the questionnaire sent to them.

One of the participants had a good level of knowledge of anaerobic digesters, but this information was based on systems from the 1970's and so now considered his knowledge to be out-dated. They are denoted below as having a H/L level of knowledge (Table 4.4).

Table 4.4. Opinions of farmers interviewed on anaerobic digesters and the level of knowledge they had on anaerobic digester prior to interviewing. RE = renewable energy.

Interviewee	A*	B*	C	D	E	F	G
Level of knowledge (**H**igh or **L**ow)	H	H	L	H/L	H	L	L
Have considered a digester (**Y**es or **N**o)	Y	Y	N	N	Y	Y	N
Currently generate RE? (**Y**es or **N**o)	Y	N	Y	N	N	Y	Y
Interested in investing in RE? (**Y**es or **N**o)	Y	Y	Y	Y	Y	Y	Y

***** Two interviewees present at interview

Those words most frequently used by the interviewees during the course of the interviews were identified using Nvivo software. This data was then used to help assign a level of importance to certain topics for the discussion of the qualitative results (Figure 4.7). The node topics and the number of times each was referred to are listed below (Table 4.5); these data demonstrate the level of interest or importance assigned for each topic.

Relevant quotations were identified from the interviews, and are included within the discussion section to help support, add detail, and expand on ideas explored to address the main aims of the chapter.

Table 4.5. The number of references collected for each node to help formulate qualitative discussion. All nodes included references from all interviews (sources = 7).

Node title	Number of references	Number of sources
Farm characteristics/ features suitable for using anaerobic digesters	86	7
Barriers towards implementing anaerobic digesters	216	7
References about the Government	44	7
Availability of information on energy technologies	41	7
Farmers' knowledge about anaerobic digesters	83	7
Matching of organic farming's ethics and benefits of anaerobic digesters	71	7
References to pollution in agriculture	75	7

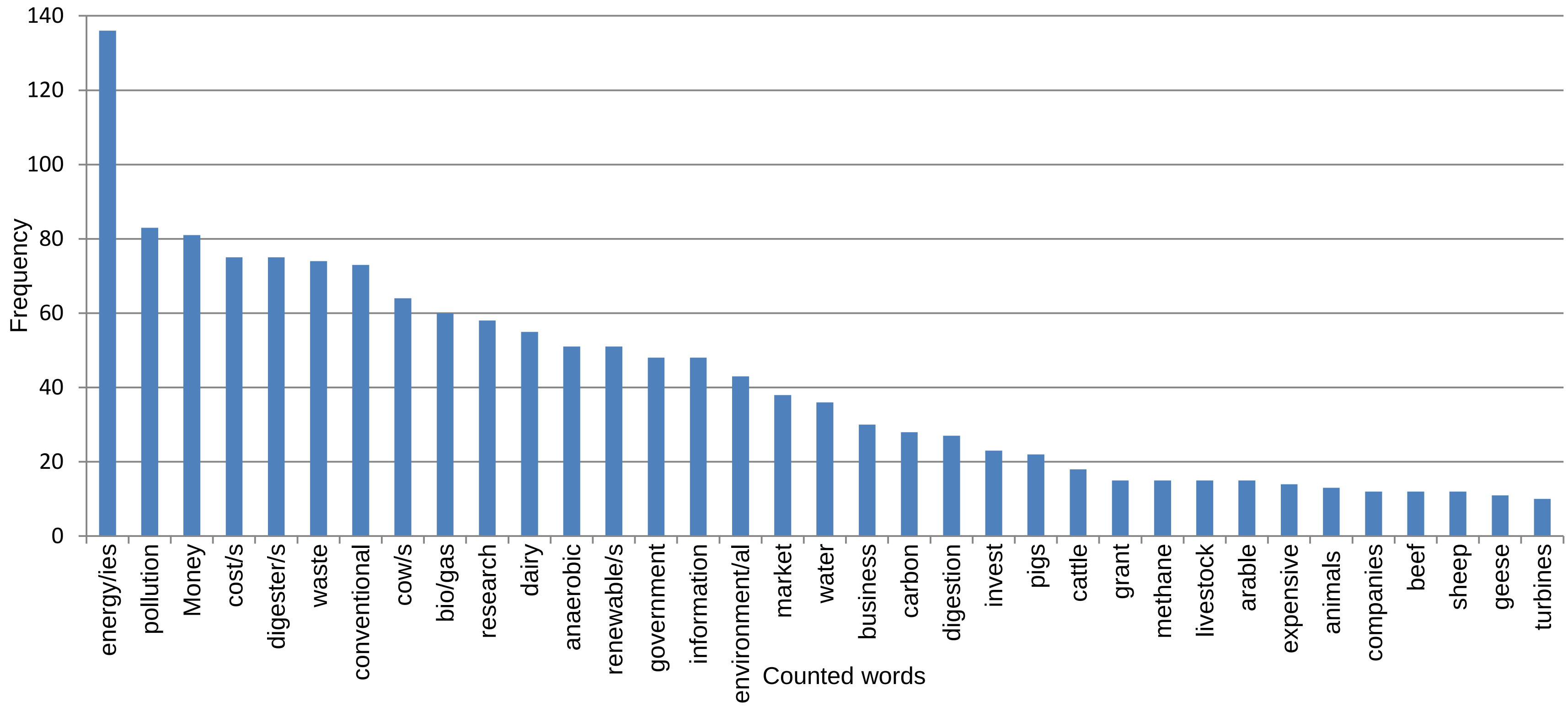


Figure 4.7 The top 35 topical words used in the farmer interviews (N=7). Energy and energies were the most frequently used word. Dairy farms and cows were the most commonly talked about farm enterprise. Pollution was mentioned more frequently than money, although there were five words referring to finances. Turbines were also frequently mentioned as an alternative renewable energy.

4.4 Discussion

4.4.1 To investigate to what extend organic farmers consider anaerobic digestion to be a suitable enterprise for organic farming.

Organic farmers may have been motivated in the past to change their farming practices due to environmental motivations (Fairweather 1999). This was also found in the current interviews;

"*The reason one goes into organic farming is to do with the fact that you want to look after the world"* (Interviewee C).

The organic farmers believe in the importance of recycling and reusing their wastes to reduce pollution.

"Organics is supposed to be using your own resources and being sustainable so obviously you are supposedly not making so much pollution" (Interviewee A1).

"*If you are polluting, you're wasting".* (Interviewee D).

From the results of the questionnaire, organic farmers rated the environmental benefits of using an anaerobic digester with more importance than the conventional farmers, suggesting they understood how anaerobic digesters could contribute to reducing environmental effects from their farm systems. Despite this, organic farmers were less likely to consider an anaerobic digester for their farms, compared with conventional farmers. This lower level of interest was contrary to predictions derived from the literature, which suggests that organic farmers are often led by their environmental motivations, which anaerobic digesters can help support (Yiridoe *et al.* 2009). It is therefore important to understand the reason for this behaviour, and to identify ways to promote the benefits and overcome the barriers.

Within the questionnaire, from the two environmental benefits that using an anaerobic digester can help deliver, reducing pollution and contamination was rated with higher importance than the benefit of reducing a farm's carbon footprint. This opinion was shared by both organic and conventional farmers. This is likely to be linked to the direct effects pollution can have on a farmer's land, rather than the less visible value of the size of their carbon footprint. Holloway and Ilbery (1996) surveyed farmer attitudes towards environmental changes. When asked for a list of environmental issues, farmers identified that applying excessive nitrates and creating pollution were among the top three rated farmer-defined environmental issues. These were considered to be rated as high because the farmers were forced to recognise them as an issue through legislation. Holloway and Ilbery (1996) defined these as “imposed issues”. Similarly, the category used within this questionnaire, “reduce pollution and contamination”, can be classed as an imposed issue. Overall imposed issues, within Holloway & Ilbery’s research, were listed more frequently as environmental issues than issues relating to “topical issues”, (those picked up in the press) and noticed changes (changes actually impacting on the farm) (Holloway & Ilbery 1996). Within this research, the topic area of reducing a farms carbon footprint may be considered a “topical change”. This may explain why it was rated of low importance to farmers compared with the benefits of reducing pollution. In addition, farmers are not penalised if they use too much energy, other than through higher energy bills, whilst polluting could result in legal action brought against the farmer.

Organic farmers rated the financial benefits from anaerobic digesters as more important than the two environmental benefits, although they rated financial benefits with lower importance compared to the conventional farmers. Organic farming has become increasingly more financially driven, especially since the introduction of incentives and premiums now offered to organic farmers (Padel 2001). This movement is often called the ‘conventionalise thesis’, and is where the eco-environmental motivation to farm organically is replaced with a capital intensive food production motivation. That does not necessarily suggest that the larger, more intensive farms do not share the same beliefs as other organic farmers regarding the environment (Blunden *et al.* 1997, Lockie & Halpin 2005). Despite this, the main peaks for growth in the organic market were in 1997 and 2000 (Figure 4.8), and were caused by a fear of unnatural GM products, which were high profile news stories at the time, rather than by increased financial incentives (Kaltoft 2001, DEFRA 2009a). Here it was a market gap, rather than a financial reward which boosted production. Financial incentives only started in the UK from 2003 as a result of the CAP reform, and again at the introduction of the Organic Entry Level Scheme (OELS) in 2007 (Natural England 2010). Financial incentives may therefore have had some impact on the responses of organic farmers. However, because the organic farmers rated financial incentives with lower importance than the conventional farmers this suggests that there must also be other reasons for the lower interest in anaerobic digesters expressed by organic farmers compared with conventional farmers.

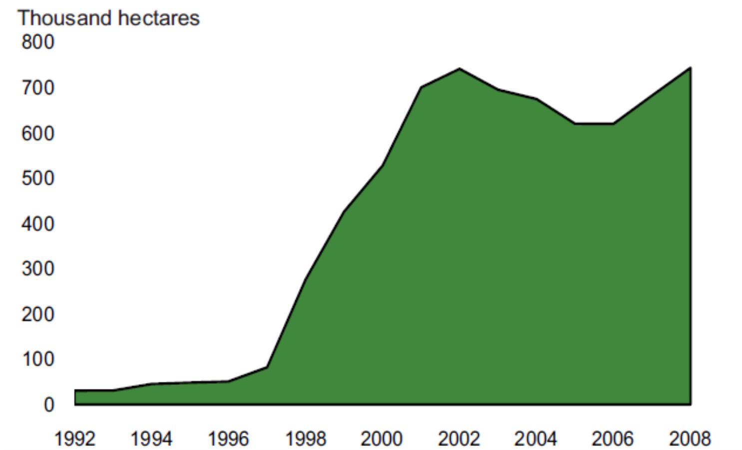


Figure 4.8. The amount of land within the UK designated as organic. The rapid increase of converted land was due to the public fear of new technologies, in particular GM, which enabled the organic market to expand. Taken from (DEFRA 2009a).

4.4.2 To identify what the barriers are towards adopting and anaerobic digester, and whether these differ for organic farmers compared with conventional farmer.

From the questionnaire, a list of barriers was provided. The most important of these were the financial barriers (establishing an anaerobic digester and the amount of profits generated). Those which differed significantly between organic farmers and conventional farmers were: that organic farmers felt an anaerobic digester would disrupt their rotations more than a conventional farmer, and that conventional farmers significantly felt there was a lack of information available. Within the interviews, the most important barriers were considered to be: finances (again, establishment and profits), that the farmer did not have the right feedstock for the digester, issues with public opposition, and that the farmer did not have enough time to research the project. For this discussion all of the financial barriers have been pooled together due to the high amount of overlap within the topic.

i) Financial barriers

When questionnaire participants were asked what they considered the potential barriers were towards adopting an anaerobic digester, both organic and conventional farmers considered the costs of establishing an anaerobic digester to be the most important barrier. An estimated costing of £400,000 for a medium sized anaerobic digester was provided in the questionnaire, with a net return of £300 ha^{-1} yr^{-1} for selling the electricity

(Appendix 1). Within the interviews, organic famers felt start-up costs were a huge barrier towards adoption, and these costs were discussed in 6 of the 7 interviews.

“(I) am certainly not interested in anything that costs a lot of money” (Interviewee D).

“*I mean the whole thing is cost really. I suspect it costs a good million pounds to make a decent anaerobic digester”* (Interviewee C).

In addition, fears of poor returns were expressed both within the questionnaire results, and from the interviews:

“I don’t have confidence that it would actually work financially” (Interviewee C)

Overall, financial issues were of a higher importance to conventional farmers, because they rated economic issues as a more important barrier (fear of not generating enough profit), as well as the most important benefit from having an anaerobic digester (increasing the farm’s profit). This suggests conventional farmers are more financially motivated than organic farmers, and therefore financial issues may have influenced the organic farmers’ behaviour less than the conventional farmers. During the period when the questionnaire was sent, there was little information available on the cost of anaerobic digesters. This was largely due to the fact that very few UK based companies produced anaerobic digesters at that time. Since then, a number of UK based companies have begun to offer anaerobic digesters at a range of prices, depending upon the system required. Quotations were requested in January 2013 from two separate companies for an anaerobic digester; based upon the same farming details provided on the information paragraph in the questionnaire the resulting cost was between £850,000- £1,700,000. These costs did not include grid connection which was quoted to cost between £70,000- £250,000 (See Appendix 7 for detailed quote). Costs are still therefore highly variable and as a result, government organisations are still working to try and reduce prices and increase the financial support available for AD technology, particularly for small scale systems (DEFRA, 2012).

In a recent Department of Energy and Climate Change (DECC) consultation, the reasons identified for the slow uptake of anaerobic digesters were the inability to access large finances for the start-up costs, and that the 8% IRR (Internal Rate of Return) was too low (DECC 2011b). Financial support through grants and incentives are available for those interested in anaerobic digesters to help them establish, and provide continuous revenue. Interest free loans are available from the Carbon Trust, to invest in energy saving equipment, and occasionally grants are available through WRAP. Farmers can also charge a gate-fee to take on organic wastes, although on organic farms this is only permitted with their certifier's permission (Soil Association 2009b). Equally, on-going revenue is available through the Feed-in-Tariffs (FITs) and Renewable Heat Incentive (RHI) schemes. Although finances may therefore be available to them, farmers commented they were confusing and complex to access (DECC 2011b). In the interviews, farmers expressed that the hassle of filling in paperwork alone was enough to put them off;

""*They don't want to get involved in the paperwork or go through the hurdle because generally these grants aren't (just a matter of) "I just need to turn up on that day and I'll get a big cheque" are they, they generally involve months and months and months of filling in forms*" (Interviewee B2).

The sustainability of incoming sources was considered a concern by the farmers interviewed. With such a long-term investment as an anaerobic digester there was a fear that the government's support for on-going incentives may not remain consistent. This has recently been the case with FITs, whereby uptake of solar technology was such a success that the tariff rates had to be reduced to cope with demand (DECC 2011b). Farmers also felt that the government's targets were not very clear, and therefore the methods by which the government showed support for certain projects (through incentives) may not be very well thought out.

"Very often you're asked to do things and the government says they will give you this money for it but actually, the figures don't really add up" (Interviewee C)

"I sometimes wonder whether [the government] know themselves exactly how efficient, I mean financially efficient they really are" (Interviewee G)

Other studies have highlighted the financial issues linked with investing in on-farm enterprises. The continuity of the farm can only occur if there is financial security, and therefore is likely to be the main concern for all farmers (Social Research Assocaition 2003). Although the financial benefit (generated through profits) is often reported to be the most important factor for a farmer when adopting a new enterprise (Ilbery 1991, Bowler *et al.* 1996, Clark 2009), diversification has been reported to add nothing to their income, or may contribute only a minor source of income (McNally 2001, Hansson *et al.* 2010).

It has been proposed that both finances and the motivation to run an enterprise must be present for the maximum potential uptake of a technology, such as an anaerobic digester. For example Lynne and Rola (1988) financial security did not influence a farmer's likelihood of participating in environmentally beneficial behaviours towards soil conservation unless they also were concerned about the environment (Lynne & Rola 1988). They also found that farmers with strong attitudes towards conservation were more likely to participate than those who were financially secure but who were not motivated by conservational issues. When the farmer had a high income and a positive conservational attitude, they were most likely to participate in actions to conserve soil. Financial security clearly plays a role when considering diversification, although the link between a farmer's belief and their actual behaviours is often more complex than any single reason (Schoon & Te Grotenhuis 2000).

Excluding financial issues and a lack of concern for the environment, there may also be other issues that discourage organic farmers from considering an anaerobic digester but that have a lesser effect on conventional farmers. These are discussed below:

ii) Disruption to existing rotation and lack of available feedstock

From the results of the questionnaire, organic farmers rated the interference of an anaerobic digester on their rotation with a higher level of importance in comparison to conventional farmers. Rotation disruption was also highlighted as a concern in the DECC consultation for all farmers (DECC 2011b). Field rotation is critically important on organic farms because it helps eliminate weeds, prevent disease build up in the soils, maintain soil structure and organic matter, and allows for fertility to be built back up after harvest (Blake 1990, Lampkin *et al.* 2008). Equally, rotating with livestock allows different grazing pressures on the land (Blake 1990). The co-digestion of crops and slurry can produce a higher gas yield than achieved from a single feedstock alone (Lehtomaki *et al.* 2007). More gas yield therefore means more methane suitable for energy conversion, therefore multiple feedstock are recommended. If a farmer was expected to grow an additional crop as feedstock for an anaerobic digester, this could easily disrupt long-term existing rotations.

In addition to disruption of existing rotations, there remains a debate about which crop is most suitable for use as a feedstock. Currently maize is the most common crop used for anaerobic digesters because it has a high methane production compared with cereals and grasses (Walla & Scheneeberger 2003, Amon *et al.* 2007). Maize would not be a good option for organic farmers due to the high energy/nutrient demand of the crop (Blake

1990), as well as being less environmentally friendly compared with other options, such as grasses (Gerin *et al.* 2008). This concern was shared by the interviewed farmers:

“you could grow organic maize, but also it’s quite a hungry crop, so a lot of slurry, a lot of manure in order to produce that, and should all that nutrient go to producing energy or should it go to producing food?” (Interviewee C)

“I don’t think it works unless you put in a lot of maize” (Interviewee B1)

When grown on organic farms, cereals and grasses are usually required as feed for livestock. They may therefore be available, but the amounts available would be very dependent upon how much is required for animal feed during the winter months.

Another issue regarding growing crops to produce energy is the fuel-food debate. This is the conflict between using land to grow crops for fuel, rather than for food. With food being in demand, many blame the growth of energy crops for world-wide deforestation and the food price rise of 2008 (Rodriguez & O'Connell 2011) Although organic farming is not against growing energy crops, energy crops are not recognised as organic products under EC organic standards (Lampkin *et al.* 2008). This could mean the farmer may lose revenue, as well as have to complete a lot of extra paperwork, if claiming for OELS funding for the cropped area of land. Equally farmers from the DECC consultation felt that there should be a limit to the percentage of feedstock used sourced from energy crops, aiming mainly to use the technology for waste on the farm rather than purely for energy generation (DECC 2011b). Not all organic farmers consider energy crops as a good thing;

“*What a thing to do to good food*” (Interviewee D)

“*People have a lot of concerns about growing crops for energy or putting them through AD systems*” (Interviewee B1)

An alternative anaerobic digester feedstock is food waste. Many of the farmers strongly supported the idea of using food waste and felt it would improve waste management and landfill issues.

“*My idea was going to be to collect everyone’s food waste”* (Interviewee A2).

Whether the farmer would want to, or were permitted to, use food waste on their farms was unclear to them. Some food waste can be used, with permission from the organic certifying body, and the resulting digestate spread on their lands without compromising the farm’s status (Soil Association 2008). Using food waste would also help recover lost nutrients to the soil, but equally there could be many issues with its implementation. For example, local support might be low due to the fear of the smell, potential health and disease risks and an increase in traffic. Also there may be restrictions, due to the organic standards, regarding the importation of food waste onto a farm, and once on a farm there are potential issues relating to a fear of increase in disease in animals, and regarding potential GM contamination (Soil Association 2008).

Even though external feedstock options are available for organic farms, increasing the nutrients on a farm, by importing products and recycling the digestate back to land, may compromise the holistic balance on the farm. Also when spreading the digestate back to land, the farmer must abide by their usual nitrogen restrictions (DEFRA 2008a, DEFRA 2009d). Equally, if they sold or exported the digestate, they could be losing key nutrients, such as phosphate. Exporting (and importing) digestate will also result in more transportation emissions, reducing the environmental benefits of the anaerobic digester (Berglund & Börjesson 2006). As a result, the farm system will become less holistic and lose the ethos of recycling their organic materials. Using self-grown energy crops for anaerobic digestion will eliminate the import and export issues, but it is important the crop still remains suitable for the farm's rotation, otherwise the farmer may jeopardise the success of other organic crops used for food. Equally, removing the left over crop and stubble from the field, for use in an anaerobic digester, will increase the exposure of soils (O'Leary & Connor 1998, Heenan *et al.* 2004), especially during the winter months, and affect a range of species that rely on stubble and crop ground cover for food and habitat (Moorcroft *et al.* 2002, Natural England 2010). This change in management may also affect farm payments from the government (Natural England 2010). Further environmental assessment is required here to evaluate the effects that changing crop rotations can have on organic farms.

iii) Lack of information and evidence

The questionnaire responses varied between organic and conventional farmers in regards to their perception of the availability of information on anaerobic digesters. Conventional farmers considered lack of information as a more important barrier than organic farmers towards anaerobic digesters. This may be because: 1) organic farmers have better ways of gathering information, perhaps from their experience of converting to organic farming, or the communication networks and social structure they currently use (Padel 2001); or 2) organic farmers did not know what information was available, because they had not tried to look for information on anaerobic digesters due to a lack of interest in the enterprise, as suggested by the questionnaire results.

Before farmers can consider adopting in a new technology, they need to know something about it. Although some farmers seem to have found lots of information about renewable technologies, including anaerobic digesters, others had had little exposure to any. The interviewed farmers felt that if a farmer was interested in the technology, they would actively research more into the subject, and access information in alternative ways.

From the questionnaire, farmers that were considering an anaerobic digester had actively sought out information by attending conferences and site visits. Those farmers not considering an anaerobic digester mainly gained their information about anaerobic digesters from sources they were exposed to, rather than investigated, such as from the press or The Archers series on BBC Radio 4. As we cannot tell whether the farmer was influenced directly by the information they received, or whether their interest in anaerobic digesters had affected where they then sought information from, sources of information cannot be used to draw any conclusions in regards to how they influence a farmer to consider an anaerobic digester. As the conventional farmers were not asked where they sought their information from, no comparison can be made between the two types of farming systems. An assessment of farmers' opinions before and after visiting an anaerobic digester would therefore be an interesting study.

From the interviews, the first source of information regarding anaerobic digesters was from the press, and if the farmer was interested, they then used other sources of information;

"Demonstration days probably, demonstration days and just generally in the press so that's where I started- visiting other people and seeing how they were doing it"
(Interviewee E)

"I guess you start by reading a few articles in the farming press or whatever, and looking at websites and stuff, and you get more interested and you find a seminar or something that's going on locally you know and you decide to give a day and spend some money and go up there and you just slowly learn about it" (Interviewee B1)

The most useful and trusted sources of information came from non-profit driven organisations, such as the Country Land and Business Association (CLA), WRAP and

National Farmers Union (NFU). Generally, private companies were not seen as trusted sources of information:

"*I would just always try to go to an independent body who wasn't trying to make money out of it"* (Interviewee F)

"I just didn't believe what [the private company] *were saying*" (Interviewee G)

The participants also felt they trusted information that came from other farmers, especially if they were experienced. Information from other farmers came from site visits, seminars, or just knowing people personally within the agricultural and renewable energy sectors with whom they could discuss the subject. This also highlights the importance of creating good networks for farmers that they can use to learn about new or alternative husbandry methods. It is also an important method that researchers should use to promote their research results;

"If they've done it for a few years and they've got the scars on their backs to prove it, I would listen to them" (Interviewee B1)

Lack of information available about anaerobic digesters may also be related to the low number of anaerobic digesters that current exist in the UK. With so few plants up and running, lack of information may also be lack of evidence and confidence that the technology works. Lack of evidence was identified as a concern for farmers in the DECC consultation (DECC 2011b), and was also raised in some of the additional comments made by questionnaire participants. The lack of current running anaerobic digesters appeared to put off some of the interviewees from considering investing. They felt that without readily available information, they would have to do all the research into the technology themselves, an option not available to them due to personal constraints. They felt that current anaerobic digesters were "*at an early stage in the technology"* (Interviewee B1). Some farmers felt that they did not even believe the technology could work on their scale. This has been considered an important issue and has therefore been used to help experimental design in chapter 5.

As well as being early in their development, farmers also felt that the complexity of anaerobic digesters put them off from investing. They therefore felt a "turnkey" option would be a great advantage to them. Farmers indicated that, to as great an extent as possible, they would prefer to let an employed person deal with the details, such as seeking planning permission and locating the equipment. Here an anaerobic digester was compared with purchasing a slurry tank, or tractor, where all the complexities were dealt with by one person. This was also mentioned in the Anaerobic Digestion Strategy Plan (DEFRA 2012). This would save the farmer time and would enable them to have a final costing, rather than having to shop around, thus making business plans easier to write. Simplifying the processes would therefore make the whole investment more attractive.

"*I'd ask; how much is that going to cost? If it was reasonable, I'd give it a crack, definitely*" (Interviewee F)

"*Well if you knew that it was going to cost so much and you were going to make such and such return on your capital investment, it might, people might think- yes that's not a bad plan"* (Interviewee C)

At the time of data collection, turnkey systems were not widely available. Since then, companies now sell turnkey style digesters, for example Seab energy ®, Evergreen Gas ® and Morre Biosystems ®. DEFRA have also highlighted the need to focus on the development of small scale systems within their AD Implementation Plan (DEFRA 2010a). As there are still so few anaerobic digesters currently built within the UK, those systems that have been running for a few years are likely to have been created by pioneers and so are unlikely to have been done through one company. Now that plants can be designed and built through one company (see appendix 8 for breakdown of one companies costing for an AD plant). As more plants become commissioned and completed and farmers start to share their experiences, the success of turnkey systems will soon become better known.

iv) Public opposition

Another barrier towards implementing an anaerobic digester onto their farm commonly discussed by the interviewees was the potential lack of public support. This would have a major impact on the ability to get planning permission. Planning permission is needed when the farmer is sourcing external feedstock, while small-scale on farm systems using only their own derived materials may be passed as permitted development (NNFCC 2011). Some projects face opposition to get planning, while others, particularly those with environmentally aware planners, easily get through (NNFCC 2011). Other issues which create problems when getting planning permissions include: getting the correct licences and permits, health and safety issues regarding the safe use of an anaerobic digester and all its associated equipment, and the costs and time needed to carry out Environmental Impact Assessments (Planningforclimatechange, 2011). Those organic farmers interested in using anaerobic digesters as a method of reducing food waste to landfill believed that the potential increase in traffic would be the largest objection from the locals. From the questionnaire, not getting planning permission was the third biggest barrier towards anaerobic digester adoption. Many of the farmers' interview responses were as a result of personal experiences or from word of mouth regarding other renewable technologies (Wolsink 2007, Firestone *et al.* 2012, Rygg 2012), and they felt that anaerobic digesters would also be likely to face similar opposition.

"Most people's attitudes to wind farms are- over my dead body" (Interviewee B1)

"*You're not allowed to do anything without getting planning permission, which will cost about 20 consultants' reports and that again costs a huge amount of money, and I'm certain that the local planners would consider anaerobic digestion not something that goes on in the countryside because it is sort of an industrial process"* (Interviewee C)

The reason for public opposition towards wind farms is mainly based on the visual impact they have on the surrounding area (Krohn & Damborg 1999, Harrison *et al.* 2008, Butler 2010). Anaerobic digesters are less likely to have as high a negative visual impact, but may still suffer from opposition due to the public not understanding the technology or having NIMBY or "not in my back yard" opinions (Dear 1992, Wolsink 2000). Council run petitions against anaerobic digesters often object to planning due to increased traffic, noise, odour and visual impact. Although opposition may be common, of the 45 proposals submitted between 2006 and 2009 for anaerobic digesters, all were permitted (Butler 2010). Interviewees considered that the issues around planning permissions and lack of public support were mainly a result of the type of people who lived within the local areas being against change, and more specifically the potential increase in traffic that anaerobic digesters may create.

v) Digestate as a usable fertiliser

Organic farmers use their existing animal and crop residuals as a form of fertiliser, enabling them to complete the biological cycle and create a holistic system (Blake 1990). As a result, any possible changes in waste storage and management may concern organic farmers more greatly than conventional farmers. Analysis of the questionnaire showed that organic and conventional farmers did not differ in their views as to whether digestate would produce a worthwhile fertiliser. It has long been accepted that digestate, produced as a by-product of methane generation, can be used as a fertiliser (Myers 2006). In some cases the production of digestate is even seen as a motivation to invest in an anaerobic digester, because it is considered an "improvement of manure" (Walla & Scheneeberger

2003). Anaerobic digestion is permitted as a method of treating waste, ready for field use, in both the Soil Association standards, and the Organic Farmers and Growers Standards (OF&G 2006, Soil Association 2009b). Furthermore, regulations are now in place to ensure the quality of digestate as an organic fertiliser and this is monitored by the Renewable Energy Association through the bio-fertiliser certification scheme (REA 2011). Additional comments regarding digestate were mentioned by farmers, and are discussed below in section 4.4.3.iii.

Digesting manures causes both chemical and physical changes to the original material; therefore, replacing manures with digestate could potentially cause disruption to the soil biota, for example, earthworms. Work on this subject has been discussed in more depth in chapters 2 and 3 (fieldwork and earthworm bioassays).

4.4.3 Potential predictors of farm type and farmers whom are likely to adopt anaerobic digester

In addition to the fact that conventional farmers were more interested in anaerobic digesters than organic farmers, there were other demographic and descriptive factors that indicated a farmer may be likely to consider an anaerobic digester. Knowing what makes a farmer more likely to consider a digester means that companies or the Government can target these factors.

No characteristics from the questionnaire significantly correlated with an organic farmer's likelihood of investing. From the conventional farmers' responses, the younger the farmer, and the larger the farm size, led to an increased likelihood that a farmer would consider an anaerobic digester. Also those farmers with an agricultural education were more likely to consider anaerobic digesters. The level of education and age of a farmer has both been found to influence decisions in previous work considering diversity and changing practices on farms (DEFRA 2007a, Bailey *et al.* 2008). This is in contrast to McNally (2001) who reported negligible effects of age on the adoption of new enterprises on farms. She identified that the single most important variable to affect the probability of observing a form diversification enterprise on the farm was the presence of a spouse; although she did not separate organic and conventional opinions. Within the current data set, organic farmers were not found to be significantly more educated than conventional farmers which is contrary to the findings of previous studies (Padel 2002).

i) Farm size

Farm size was considered by the interviewees to have an effect on the likelihood of a farmer considering an anaerobic digester. Larger farms are usually considered to be more suitable for the implementation of an anaerobic digester. The perception that anaerobic digesters are larger scale enterprises is likely to be linked with the current anaerobic digester status in Europe. For example, German anaerobic digesters in 2005 had an average installed energy capacity of 1385.58 kWs. In comparison, anaerobic digesters in the UK, which were rare in number, had an average installed energy capacity of 623.46 kWs (AD-Nett 2005a). Interviewees gave reasonable justification as to why they felt anaerobic digesters on a large scale were more suitable.

"You know the bigger your farming system, the more robust it is, proportionally the less the risk with trying something new" (Interviewee B1)

"They are making money out of the big ones, but maybe there's just not enough in it for the smaller ones" (Interviewee F)

"It's mostly done, in this country as far as I can see, very large systems" (Interviewee B1)

It is well recognised that larger farms have more opportunities to diversify due to greater resources, whereas smaller farms lack resources and may have limited ambition (McNally 2001, DEFRA 2007a). This is equally the case for anaerobic digestion technology, where, for example, farmers with larger herds (>250 head) are more likely to invest than those with fewer cattle (Swindal *et al.* 2010). For these reasons, the promotion of small scale systems needs to be supported if they are able to help deliver government targets and reduce pollution. The purpose of Feed-in-Tariffs (FIT's) is to encourage non-energy professionals to invest in small scale projects with a simple, clear payment method. The payments for anaerobic digesters are scaled depending on anaerobic digester size, with units less than 250kW's, earning 14p kWh^{-1} generated, 250kW - 500kW earning 13p kWh^{-1} and those over 500kW's earning 9p kWh^{-1} (DECC 2011b). Here at least there is evidence of additional support for smaller farm systems, by having higher tariffs, but whether these are financially enough is debatable.

A link between herd size and interest has previously been identified, although farms with fewer than 250 head of cattle have been considered to be too small to be economically viable (Swindal *et al.* 2010). In the current report, conventional farmers with over 130 head of cattle were more likely to consider an anaerobic digester, compared with farmers who kept less than 130. Organic farmers did not show this trend.

ii) Farm types

From the questionnaire data, farm “type”, i.e. dairy or crop based, had no significant effect on the likelihood of a farmer who is considering adopting an anaerobic digester. The most common organic farm types for which a farmer would consider an anaerobic digester were dairy and mixed farms, and the most common conventional farm types were dairy and pigs /poultry farms. Similarly, Bailey *et al.* (2008) also demonstrated that farmers of dairy, pig/poultry and mixed farms were the most interested in biogas options. Generally, dairy farmers are likely to be interested in energy efficient activities but are less likely to consider investing in alternative enterprises, due to the intensive workload involved in running the farm on a daily basis (Bailey *et al.* 2008). Alternatively, arable cash crop based enterprises have seasonal working periods and so may have more time available for alternative enterprises (Ilbery & Bowler 1993, McNally 2001, Masse *et al.* 2008).

Slurry is a major by-product of dairy farms (Smith *et al.* 2007); therefore, the opinions of those farmers that responded positively to the question asking whether they had a slurry problem can be used as a proxy for the opinions of dairy farmers. The number of organic farmers claiming to have a slurry problem was too low for meaningful analysis; therefore, the data for organic and conventional farmer responses were pooled. With a larger number of responses, it was possible to identify farmers with slurry problems were more likely to consider an anaerobic digester- although whether this was linked to improving waste management options on the farm is unknown. As dairy farming is responsible for large methane emissions, one option for them is to capture the methane through anaerobic digestion. It may be an incentive for the farmer to deal with their slurry using an anaerobic digester if they are likely to face financial penalties from the Environment Agency for poor management (DEFRA 2009b). Reducing pollution is considered an imposed issue (Holloway & Ilbery 1996), and with the NVZ regulations now in place (DEFRA 2008a) it would therefore make sense for farmers to consider other options to best manage their slurry situations.

The interviewees were asked to consider which farm type would be the most suitable upon which to locate an anaerobic digester. Suitability was not defined for the farmers, but was considered to be a farm that had access to feedstock, and available money, time and labour. When the participants were asked about the suitability of anaerobic digesters for farms, they indicated that dairy farms were the most suitable enterprise for an anaerobic digester.

"Dairy farmers produce the most amount of slurry because they bring the animals in every day- there is a constant supply of slurry, in terms of yard washing and cattle standing around produce faeces, yeah I think that you might look very seriously closely at putting in something in" (Interviewee C)

"Yes and that's why I think dairy farms they aren't going to need much to persuade them what with the rising costs and things " (Interviewee A1)

Although dairy farms appear to be the most suited farm enterprise for an anaerobic digester due to their practical suitability, and due to the farmers' ability to use the products generated within the farm system, slurry itself offers a low biogas potential. Slurry produces only 15 - 25 m^3 per fresh tonne of material, compared with other organic materials, such as grass silage which produces 160 - 200 m^3 per tonne of fresh material, or poultry manure, which produces 80 m^3 per fresh tonne (NNFCC 2011). This means for the size of the investment required, dairy farmers are likely to get the lowest financial return per tonne of material processed. Net profit, compared with their existing management options, i.e. using generated energy on-site to replace bought in energy supplies, may influence farmers more and should be promoted in these cases. As a result of the interviewees considering dairy as the most suited farm enterprise for an anaerobic digester, a dairy case study was chosen for chapter 6.

iii) Industrial use

Farmers did not consider anaerobic digesters to be solely an agricultural technology, and felt that reducing pollution via anaerobic digestion was not only the responsibility of agriculture. This was particularly apparent in the farmers' comments on the subject of food waste which they suggested that could be used as a feedstock. Agricultural businesses were considered not to be financially secure enough to take such large financial risks.

"But it's really a small industrial process, I don't see it as being an organic process or even a particularly a farming process actually" (Interviewee B1)

"And farming businesses are not strong. They are generally very weak and marginal businesses. So they are absolutely the wrong kind of business to be asked to take this sort of risk" (Interviewee B1)

Although the UK agricultural sector currently produces the most methane (Smith *et al.* 2007), other sectors, such as landfill, also emit methane. Food waste could be redirected from landfill and be treated by anaerobic digestion. As anaerobic digesters also produce digestate as a by-product, agricultural land is the best way to dispose of this material. Therefore, although the technology may not be an agricultural issue, by being able to dispose of the digestate onto agricultural lands, rather than it being treated and disposed of in another way, the waste cycle can become sustainable. Equally, agriculture can benefit from digestate imports by reintroducing nutrients to soils. In addition to reducing waste to landfill, the biogas yield from food waste products can be 10 times the amount generated from cow manures (Weiland 2000, Weiland 2010). Introducing food waste digestate into agricultural systems is more complicated than if the feedstock was created on-site at the farm, due to the fact that the material is defined as a "waste" product. Steps for this process are already in place through the Quality Protocol (QP) and the PAS110 (WRAP 2008) whereby "waste" products can be re-categorised so they are no longer "waste".

iv) Organic status

Some of the reasons behind farmers' choices for adopting an anaerobic digester were linked to a farm's organic status. It was not clear from the interviews whether anaerobic digesters were suited for organic farms as both organic farmers' practical and emotional motivations behind adopting would differ. Overall, the farmers thought the technology was better suited on conventional farms. This was because conventional farmers had a wider range of waste management options available to them compared with organic farmers. Organic famers also felt they were doing a better job of managing their waste than conventional farms. Conventional systems are also bound by fewer constraints in comparison to those that are set out by organic certifiers, have the ability to grow more suitable crops, and already have financial incentive in place. In addition, organic farming already uses more land space than conventional agriculture for the same yield output and farmers felt that encouraging the use of even more land for the growth of energy crops may be inefficient. It has also been commented on elsewhere, that the sustainable land available may not be large enough for the co-production of energy and food (Muller 2009). In the interviews organic farmers felt that organic status would make it less likely that a farmer would consider adopting within the next 5 years, in comparison to a conventional farmer.

"I think the inorganic farmers would be better for the point of view that they would do it for the money… but the organic farmers would be better as they would be doing it for the… because it is the right thing to do" (Interviewee F)

"They've done nothing to use the slurry as a resource to produce methane, although it does produce methane just like that" (Interviewee C)

4.4.4 Areas of interest that require further investigation regarding the slow uptake of anaerobic digesters on organic farms

There exist a number of improvements that can be made to the anaerobic digestion sector to increase its status and success. The interviewed farmers wanted quality research they trusted and understood. They wanted to talk to farmers and see anaerobic digesters working for themselves before they would consider investing. Knowledge exchange is therefore crucial to promote the technology within the agriculture sector. They want reassurance that the technology works, both practically and financially. This evidence is difficult to provide on a farm by farm basis. Therefore the best way to access this information is to use calculating tools, such as the NNFCC's *AD cost calculator,* or the University of Southampton's *Energy and Emissions calculator* for on-farm anaerobic digesters (Salter 2011). By using these tools, farmers can evaluate their own farming system to see if it is suitable, or identify what changes they would need to make, for example the need for an additional feedstock source.

The farmers also demonstrated they understood that anaerobic digestion is a business driven technology, and that they wanted market security for their investment, whether that was through financial incentives or market sales of products produced. The current perception of anaerobic digesters in the UK has been influenced by the large systems that are used in Europe, which has led many farmers to disregard anaerobic digestion as a potential energy technology. European systems on this scale and feedstock use, appears to have given anaerobic digesters bad press with regards to their suitability for many UK farms.

"I believe the energy produced from maize crop for example is far better than the energy produced from slurry, there's no doubt about that and I know of a number of German units that have given up their cows now and they just produce maize to put into their plant and its relatively simple, and they get a bit of slurry from time to time to keep the liquid right" (Interviewee E)

To address the negative impression farmers currently have towards anaerobic digesters, the market needs to re-advertise the improved anaerobic digestion technology, which is now more suitable for UK farms.

4.5 Conclusion

The key findings of the chapter are the identification of a number of barriers towards adopting anaerobic digestion technology, for organic and all farming types.

- Financial issues were identified in both the interviews and questionnaires as the main reason for the slow uptake of anaerobic digesters on organic farms. Reasons given from the interviews included the Government not understanding the current anaerobic digestion market, and that subsidies did not appropriately reflect the level of risk associated with anaerobic digesters.

- Organic farmers were less likely to consider adopting an anaerobic digester than conventional farmers, even though they considered the environmental benefits of anaerobic digesters to be more important in comparison to the responses from conventional farmers.

- Dairy farmers were thought to be more likely to adopt anaerobic digesters than any other farming enterprise. This was considered to be the case for a number of reasons:

    - They had more slurry issues than other farmers, which was an indicator of increased likelihood of adopting an anaerobic digester.
    - Dairy farmers have a readily available feedstock in the form of slurry, without the requirement to grow additional material.
    - Dairy farms are responsible for generating high methane emissions. Here an anaerobic digester could create an opportunity to reduce methane emissions.
    - The dairy farmers would be able to make the best use of the energy generated on-site, thereby reducing outgoing energy costs and dependence on the Grid and as a result, reducing their farms' total carbon footprint. By how much a dairy farm could benefit from both energetically and environmentally from an anaerobic digester is case dependent, and explored in more detail in chapter 5.

- Organic farmers feared there would be problems if they considered importing feedstock for an anaerobic digester. The interviewees felt that importing other feedstock could create positive financial opportunities for conventional farmers.

- Anaerobic digesters should be promoted to farmers with existing environmental issues, such as those with slurry storage issues. This may include conventional farmers where any environmental improvements to the farm system could be magnified compared with changes on an organic farm.

- Younger farmers were more likely to consider investing in anaerobic digestion, and are potentially a group to target to promote the technology through education; especially those still in agricultural college.

- The information available to farmers was not considered easy to access. They felt the majority of the research into the technology needed to be done by the farmer themselves. The internet and the press are often an initial source to generate interest. Private companies were considered the worst source for information, as they were seen as profit driven and therefore did not have the farmers best interests at heart.

- All the farmers interviewed showed an interest in renewable energy generation. They felt that anaerobic digesters fit within the organic ethos, but whether they fit practically for each farm was a separate issue.

- The participants considered anaerobic digestion to be an industrial process, rather than an agricultural one, and therefore should be used to address landfill and waste issues from organic materials such as food waste, rather than just for treating agricultural wastes.

Chapter 5

Assessing the impact an anaerobic digester can have on a farm's carbon footprint

5.1 Introduction

The definition of a carbon footprint varies between sources. This variation is often dependent on which gases are measured and which units are used (POST 2006, Weidman & Minx 2008, The Carbon Trust 2012). Here, the Carbon Trust's definition is used. This is;

"*the total greenhouse gas emissions caused directly and indirectly by a person, organisation, event or product*" (Carbon Trust 2011).

Numerous approaches for calculating carbon footprints are now commonly used; from life-cycle assessments of individual products, to input-output based methods (Weidmann & Minx, 2008). As the term carbon footprint becomes commonplace, individuals are more aware of their own sources of Greenhouse Gas (GHG) emissions, with many interested in methods to reduce them. As a result, there is a wealth of advice available on methods to reduce carbon emissions (POST 2006, The Carbon Trust 2012, Carbon Footprint 2013). In addition to reducing GHG emissions from the source, replacing fossil fuels can also reduce an individual's carbon footprint.

Worldwide agriculture was responsible for creating 5.1 - 6.1 gigatons of carbon dioxide equivalent (CO_2 equiv.) in 2005 (DECC 2011c). Agriculture in the UK created 51.9 megatons CO_2 equiv. in 2009 (DECC 2011c). This was mainly through land management issues, including land use changes, and through livestock and manure management (Smith *et al.* 2007). The most common GHGs emitted by the agriculture sector are carbon dioxide (8%), nitrous oxide (55%) and methane (37%) (DECC 2011a). Other gases considered to be GHGs include Hydrofluorocarbons, Perfluorocarbons and Sulphur hexafluoride (United Nations 1998), but are not discussed within this chapter as they are rarely produced by agricultural activity. Although ammonia is also a known gaseous agricultural pollutant (Sommer & Hutchings 1995, Amon *et al.* 2001), it is not considered a GHG within the Kyoto Protocol (United Nations 1998), and is excluded from this chapter.

5.1.1 Manure management

Manure management is responsible for 5 - 30% of the global methane emissions from agriculture and highlights an area where improvements can be made (Sommer & Olesen 2000, Svensson & Pell 2001). Intervention can occur at any stage within the manure management process (Figure 5.1). Any alterations in management can have knock-on effects on the amount and type of emissions at later stages (Weiske *et al.* 2006). There are many reviews available on manure management methods, including methods to reduce GHG emissions associated with the spreading and storing manures (Weiske *et al.* 2006, Karakurt *et al.* 2012). Anaerobic digesters, for example, can alter how manures are stored, which then can impact on the amount of GHG emitted at later stages of the manure management process (see section 5.1.2 below).

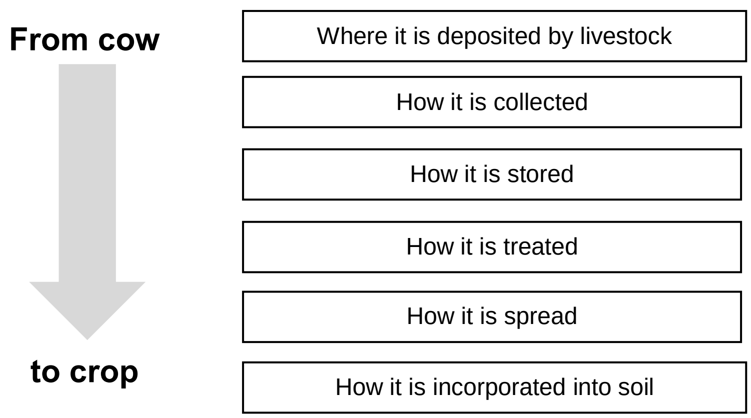


Figure 5.1 Stages involved within manure management process for farmers recycling their manures back to land. At each stage of the process, changes in practice can be made to reduce total GHG emissions from organic material. Within this chapter, the impact anaerobic digestion can have on manure management focus on the stages of "how it is stored" and "how it is treated". It can also have knock on effects on the total GHG emissions, on how "it is spread" after treatment and "how it is incorporated into soil".

Dairy farming is considered to be the largest GHG emitter in UK agriculture. This is mainly from enteric fermentation, but also from manure management, in particular slurry storage (Weiske *et al.* 2006). Enteric fermentation is the breakdown of carbohydrates by microorganisms which release methane as a by-product. This process occurs in animals with a rumen, for example cattle, who then release the methane through belching or flatulence. In 2008 there were 10,378,000 cattle in the UK, creating an estimated 146 million tons of slurry per year (Holm-Nielsen *et al.* 2009). Amon *et al*. (2006) studied the emissions resulting from dairy cattle slurry and slurry management. They found more than 90% of the net total emissions originated from the methane emitted during storage and therefore concluded that abatement efforts to reduce emissions would be most effective if used during this period. One of the simplest methods to reduce emissions is to cover stores (Sommer & Olesen 2000, Amon *et al.* 2006). Currently, lagoons are the most popular method of slurry storage, with 50% of farms using them in 2011. Of these, only 1% were covered (DEFRA 2011a). In addition, 47% of UK farmers used slurry tanks for storage; and of those, only 11% were covered (DEFRA 2011a). As of 2011, 26 farms used an on-site anaerobic digester (NNFCC 2011). This is only 2.6% of the National Farmers' Union's target of 1000 digesters on farms by 2020 (National Farmers Union 2009). There is therefore some way to go to improve UK slurry storage methods.

Aerobic composting can help reduce the uncontrolled release of GHG emissions by making the material more stable (Amon *et al.* 2001) and is often used on organic farms as a method of treating organic wastes (Lampkin *et al.* 2002). The storage management of the manures and slurries can also have an effect on the GHG emissions they emit when spread (Wulf *et al.* 2002b). The emissions generated by spreading also differ depending on the methods used and the land type it is applied to. Wulf *et al*. (2002b) found that more nitrous oxide was emitted when slurry was injected into grasslands, compared with arable lands. Also the total carbon equivalent emission for different organic fertilisers did not differ when spread to arable lands, although they found a differences in the types of gases that were released (2002b). Currently, 90% of UK farms spreading slurry use splash plate methods (DEFRA 2011a). Although this may result in lower nitrous oxide emissions compared to injection application, the CO_2 equiv. is similar to that of injected application (Wulf *et al.* 2002b). Methods of application therefore should be matched to the field conditions and type of materials spread.

Environmental factors can affect GHG emissions. Wulf *et al*. (2002b) noticed that differences between the composition of the gases and the period when they were emitted depend on the land type over which the material was spread. Compounding effects of seasonality and manure management cause further complications when making predictions of GHG emissions for different farming practices (Amon *et al.* 2001, Amon *et al.* 2006, Clemens *et al.* 2006).

5.1.2 Using anaerobic digesters within manure management

In their 2008 report entitled "*Building a low carbon Economy*", the UK Committee on Climate Change recommended three on-farm abatement opportunities for reducing emissions (Committee on Climate Change 2008). With regards to agricultural waste, they recommend,

"*capturing methane from manures and farm wastes and using anaerobic digestion to produce energy from it*" (Committee on Climate Change 2008).

Anaerobic digesters are now a widely accepted method to reduce carbon footprints by reducing manure emissions and substituting biogas for fossil fuel-derived energy (Amon *et al.* 2006, Johnson *et al.* 2007, Bertora *et al.* 2008, Yiridoe *et al.* 2009, Tranter *et al.* 2011).

The GHG emissions during the storage and application of digested manures differ from undigested manures. Carbon equivalent emissions can be reduced in both the spread and storage of digestate (Wulf *et al.* 2002b, Amon *et al.* 2006, Clemens *et al.* 2006, Maranon *et al.* 2011) as well as having a knock on effect to other stages of manure management (Figure 5.1). The gas emissions composition differs after digestion, with more nitrous oxide released from digested slurry, than undigested; and more methane released from untreated slurry, than digestate slurry, although total carbon equivalent of the two is still lower from the digested slurry (Wulf *et al.* 2002b, Amon *et al.* 2006). It is therefore important to consider the whole manure management process when calculating GHG emissions from incorporating an anaerobic digester (Weiske *et al.* 2006). Within this chapter, manure management stages after 'how it is treated' (Figure 5.1) are considered, although the practical application of an anaerobic digester onto a farm should consider all stages. For example, 'how it is collected' would be important if a farm was trying to maximise feedstock, and as a consequence gas production, from anaerobic digestion.

Further emission savings could be made by replacing existing fossil fuel-derived energy use with biogas powered energy (Tafdrup 1995, Banks *et al.* 2007, Salter & Banks 2009). Biogas, for example, can be used to generate heat and electricity in a Combined Heat and Power (CHP) unit, or upgraded and compressed to provide a substitute for natural gas. This can then be used to supply homes and industry as a fuel source or used in vehicles (Hansson *et al.* 2007). Further details of the use of biogas can be found within chapter one, section 1.4.3.

By increasing farmer awareness of the environmental benefits that an anaerobic digester can deliver, more farmers may be encouraged to invest (Yiridoe *et al.* 2009). Although financial considerations are frequently identified to be the main decision making factor, as discussed in chapter four, farmers also want to be reassured of the environmental and energy value from the system.

The feedstock used by an anaerobic digester is not restricted to animal manures. Alternative organic materials, for example crop residuals, spoilt crops or crops grown specifically for anaerobic digestion can also be used (NNFCC 2011). Additional feedstock can increase the volume of biogas produced whilst making use of the other organic material residues around the farm. Farmers may also consider importing materials to boost gas. This could further reduce the GHG emissions associated with UK agriculture, although may not necessarily reduce the carbon footprint of the farm itself. Factors such as the distance of the imported material, the type and amount of feedstock, and whether the farmer uses the biogas produced onsite would all need to be considered to see if it is worthwhile.

5.1.3 Aim of this chapter

The aim within this chapter is to understand to what extent an anaerobic digester can benefit a farm's carbon footprint. This is in terms of both the total carbon equivalent GHG emissions produced and the ability to replace fossil fuel-derived energy with renewable energy. This question was identified by farmers from chapter four who wanted to know whether an anaerobic digester was both an energy saving and environmentally worthwhile investment. Two organic farm case studies were chosen, one dairy and one mixed farm. The values used within the analysis come from a number of sources and vary greatly. The data should therefore only be used as a guide to identify trends, rather than to provide an accurate value of carbon emissions for the farm case studies (Pain & Jarvis 1999, Amon *et al.* 2001). The main objectives of the chapter are to:

1) Create two case study scenarios; one organic dairy and one organic mixed farm; to assess the impact an anaerobic digester could have on their total carbon emissions. A baseline emission value was compared with values generated from multiple scenarios that incorporate an anaerobic digester.

2) Identify whether the case study farms could become more self-sufficient in energy. The dairy farmer chose to convert the biogas into electricity to replace imported electricity. The mixed farm chose to use a calorific equivalent value of diesel, with the intention of upgrading and compressing the biogas into bio-methane.

3) Highlight the limitations an anaerobic digester has in reducing the case studies' total farm GHG emissions.

5.2 Methods

5.2.1 Measurement and calculation of emissions

The carbon footprint measured here considers a top-down environmental in-put out-put analysis. It is based on GHG emissions from the machines and livestock of the farms as seen on a day to day basis (Weidman & Minx 2008). The emissions created from the production of machines, non-farm buildings and human-generated power, for example, are included. The emissions generated from building the anaerobic digester are also excluded. The GHG emissions are expressed as a measure of total CO_2 equiv., rather than considering each gas independently. This is a conventionally accepted method, and are measured in either kilograms (kg) or tonnes (t) (Carbon Trust 2011). The three main gases used within the farm calculations are carbon dioxide, methane and nitrous oxide as are the most common gases emitted from agriculture. The value for each gas is determined by its Global Warming Potential. In accordance with the IPCC values for 20 years (2006), one tonne of carbon dioxide = one t CO_2 equiv., one tonne of methane = 25 t CO_2 equiv., and one tonne of nitrous oxide = 298 t CO_2 equiv.

For the purpose of this chapter, the system boundaries for the carbon equivalent analysis are set to include the general day-to-day agricultural activities that occur on the farms. These have been outlined within the descriptions of each of the case studies. It includes the emissions associated with the direct use of fuels (both liquid and electricity) on the farm to run machinery and also considers the emissions created by the livestock on the farm through enteric fermentation and manure management (all stages of figure 5.1). The analysis excludes the production of machinery, buildings and the anaerobic digester. It also excludes the production or sourcing of food for animals and humans working and living on the farm.

5.2.2 Sources of data used for calculations

Data for calculating GHG emissions were sourced from three locations; the literature, the farm owners, and from the University of Southampton *On-Farm Energy and Emissions* calculator, which is able to predict GHG emissions from basic farming data using national standard values collected from a range of sources (Salter & Banks 2009, Salter 2011). To improve accuracy, data collected from the farmer was used in preference, followed by the values within the model, and lastly, the values available in the literature.

The model is unable to incorporate all the complexities of each case. As a result, calculating exact values for each stage of the manure management process is difficult. Models are used to make satisfactory approximations, based on approximated data. For example, the emissions from cows can be calculated with greater accuracy if the cow's diet is known. Also species type and age of the cow has an effect (King *et al.* 2011). Equally, environmental effects can impact on the calculations of emissions for stored manures (section 5.1.1). The figures used within this chapter are approximations and can only give an overall impression of the total carbon footprint and the potential impact anaerobic digesters can have on the farm systems of each case.

i) Case study data

Initially, five of each farm type from the Soil Association's (SA) list were approached via an invitation letter to participate within the study. The farms that responded first (first dairy and first mixed) were chosen as case studies. A dairy farm was chosen due to the group's potential to reduce emissions (see section 5.1) as well as being considered the most likely farm type to invest in an anaerobic digester (see chapter four). A mixed farm was chosen due to their high association with and frequency of occurrence in organic agriculture (see chapter four). These farmers were sent a questionnaire of their current farming practice (Appendix 4). The data were then discussed with the farmers in face to face interviews. Information on the farm was collected including crop and livestock types farmed, machinery used, and usual manure management practices. The information was fed into the *On-Farm Energy and Emissions* calculator during the interview, allowing information on the farm's carbon footprint to be calculated from the farmer's current energy use, allowing the results to be available to them immediately. The farmers were also given the option to see what effect the inclusion of different crops and importing feedstock would have on their total energy generation.

A report was created after each interview detailing the scenarios discussed. This included the farm's potential energy outcomes from the biogas in the form in which they felt would be most suitable for their system (Appendix 5 and 6).

Energy units were expressed in terms of kilowatt hours (kWh) rather than Gigajoules (GJ) as this was a more familiar unit for the farmers and therefore more suitable in achieving the aims of the reports produced for them. Currently, both are used within the literature and for practical application on websites.

ii) The On-Farm Energy and Emissions calculator, University of Southampton

A number of tools were investigated to identify the most suitable for the purpose of the study. Two main tools were available online. The first was the "*AD Cost Calculator*", produced by The Anderson Centre on behalf of the NNFCC. This enables the researcher to assess the economics of an anaerobic digester including the capital costs, profits and percentage returns (NNFCC 2011). A lot of information was required from the farmer to run this tool and therefore would have taken longer to complete on-site than other options. Also as this study is not focusing on the economics of an anaerobic digester, the second tool, the *On-Farm Energy and Emissions* calculator (Salter 2011) was found to better suit the aims of the research. This has been developed as a method for farmers to create an energy and emissions assessment of their farm, with or without an anaerobic digester. This was the only calculator at the time offering information of GHG emissions within its calculations. It was also possible to contact the designer to find out information with regards to default values and alter them accordingly to ensure the figures represented organic farming. Within this chapter the calculator is used to aid GHG emission calculations for farming practices, in order to determine the size of anaerobic digester possible using the feedstock available and to calculate emissions and energy values resulting from the use of the anaerobic digester.

Currently, the model accounts only for the carbon costs of the electricity and diesel used within the machinery on the farm. This excludes emissions caused by enteric fermentation, storage, crop production and land use changes. As organic farmers are typically interested in all environmental factors, and therefore different sources of GHG emissions, the exclusions above were calculated for these two case studies.

iii) Literature based data

Data that were unavailable from the farmer or from the *On-Farm Energy and Emissions* calculator were sourced from peer reviewed journals. Data that best matched the farms' practices were used in preference to other values, as were data based on UK farms due to climatic and husbandry differences (IPCC 2006). Where available, multiple sources were used and their maximum and minimum values incorporated into the scenarios. This led to a large range in values for dairy farming and meant that only trends in the case studies can be considered, rather than the actual carbon footprint values calculated. Where the literature source did not provide a full breakdown of the data for each manure management stage considered their total values were used as a comparison to see if the individual values were feasible. This was particularly the case for emission data available on manure storage and spreading. The literature used for each of the values is discussed in more detail below and included in tables 5.4 and 5.6.

5.2.3 Construction of the scenarios

A baseline value for each of the farms' CO_2 equiv. footprint was calculated using the *On-Farm Energy and Emissions* calculator based on how they currently operate. This was the value used to make comparisons against the scenarios.

The scenarios were constructed using a three staged approach as shown in figure 5.2. From this, four scenarios were created for the dairy farm (Table 5.1) and five for the mixed farm (Table 5.2). Stage one considered using an anaerobic digester as a form of manure management only (stage 1 in figure 5.2). This stage addressed the carbon emissions caused and the savings made by using an anaerobic digester and is scenario 1 for both case studies. Stage two involved using the gas produced to replace energy used on the farm, including the energy required to power the anaerobic digester. The use of external energy was presumed to be from fossil fuel-derived sources (stage 2 in figure 5.2). The final stage considered the potential of importing materials to maximise gas production and to further increase energy sustainability on the farms. Excess gas produced could therefore be exported to be used off-site with the intention of further replacing fossil fuel-derived and contribute towards national energy targets (stage 3 of figure 5.2).

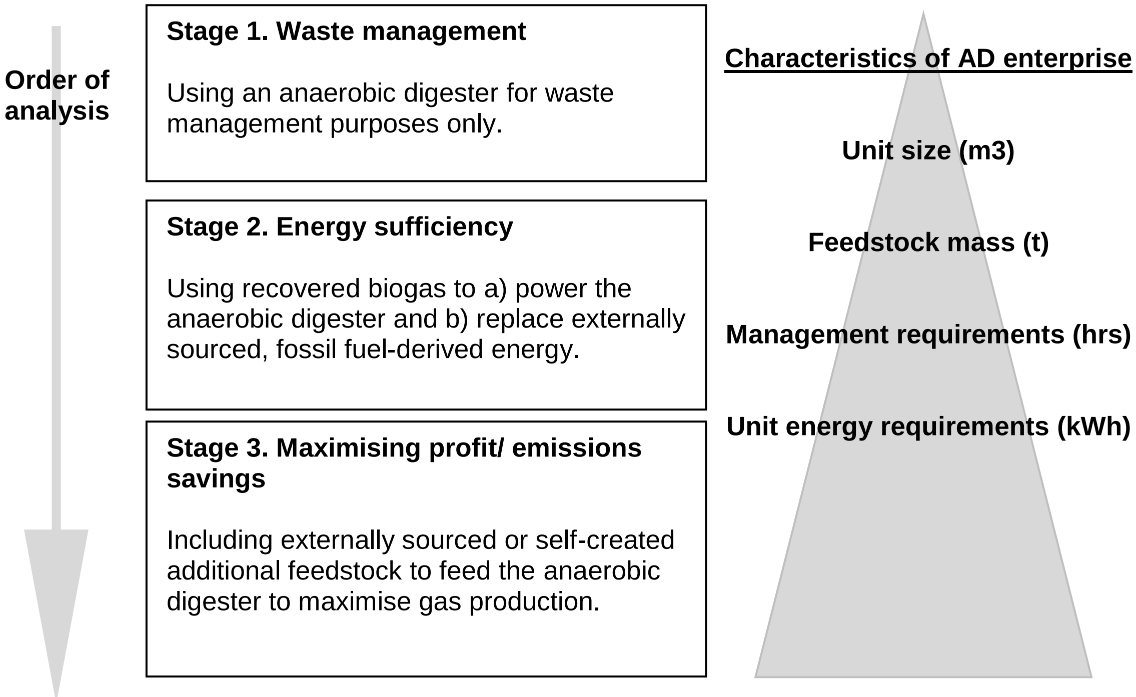


Figure 5.2. A three staged approach used to analyse the data (as detailed above). As the scenarios increase with complexity, many characteristics of the enterprise as detailed in the triangle also increase. AD= anaerobic digester. As the analysis progressed, the values for the characteristics of the anaerobic digester increased.

5.2.4 Case 1. Dairy farm

The dairy farm used was made up of 101 ha of permanent grass; of which 50 ha was grazing land and 51 ha was used for clamp silage. Livestock consisted of 70 adult Friesian cows; housed 50% of the time, and 42 followers; housed 33% of the time. Follower cattle (young cattle) were not included within the analysis due to the lack of data regarding their ages and details of their duration on the farm. The farm had a dairy parlour and was considering investing in an electric milk delivery float. As electricity usage for both processes was available, both were included within the case study scenarios. A summary of the energy use for the farm is included in table 5.4 and used to calculate the baseline value.

Four scenarios were run through the *On-Farm Energy and Emissions* calculator, based on the current farm system with the addition of an anaerobic digester in accordance with the three staged construction process detailed above (section 5.2.3, figure 5.2). Their effects on carbon equivalent emissions on the farm were calculated and compared with the values calculated from the baseline case. Scenarios 1 - 4 are outlined in table 5.1 and discussed in more detail below.

Table 5.1. Scenarios for dairy farm case study. Details of energy requirements are available in table 5.4. for the farm activities, and table 5.3 for the anaerobic digesters for each scenario.

		Scenarios			
Details	Baseline	1	2	3	4
Using the farm's 560m^3 of slurry in anaerobic digester		X	X	X	X
Using biogas produced to power anaerobic digester			X	X	X
Using biogas to power parlour and milk float on the farm				X	X
Importing 1000t chicken manure as feedstock					X

1. Incorporating an anaerobic digester as a method of manure management on the available slurry feedstock only. This scenario is unlikely to happen but is used here as the first stage of the analysis. The gas collected for this scenario would not be used as an energy source but would see the removal of emissions previously released while slurry is kept in storage. This biogas could be burnt off, although this would in turn release CO_2 into the environment and would be an improbable use of the gas. This option would still be better than releasing the methane collected alone. Energy to power the anaerobic digester would be sources from the Grid. Papers have quoted around a 50% reduction in emissions after digestion treatment compared to prior digestion (Maranon *et al.* 2011).

2. Running the current farm system with an anaerobic digester fed on the currently available feedstock and using the collected gas as the fuel source for a CHP unit.

3. Using the biogas produced through an anaerobic digester fed on the current feedstock available to supply a CHP unit larger enough to use all of the biogas produced. Energy generated would primarily power the anaerobic digester, with any surplus used to power the milking parlour and milk delivery float, eliminating the need to use external power from the Grid.

4. Using additional feedstock in the form of 1000 t of poultry broiler waste. This was available from a neighbour's farm and would increase the amount of feedstock for the anaerobic digester. Chickens emit only a small fraction of methane during their enteric fermentation and waste due to them being solid (Wathes *et al.* 1997, EPA 1999) and so no figures for methane emissions were found. Instead chickens emit high amounts of ammonia (Pain & Jarvis 1999). Chicken waste emits a lot of methane when digested (NNFCC 2011). The biogas would be used in a CHP to generate electricity to power the anaerobic digester and then farm activities. A further reduction of total GHG emissions could be made by treating chicken manure in addition to their own farm's feedstock, further reducing the carbon footprint associated with agriculture. A larger anaerobic digester and therefore more energy would be required to run this anaerobic digester.

5.2.5 Case 2. Mixed farm

The mixed farm grew multiple cereal crops on rotation over 604 ha of land. Crops grown include wheat, spring barley, triticale and rye; as well as beans, clover and other green manures such as vetch and mustard. The farm's livestock consisted of 200 beef cattle, housed 40% of the time. Livestock manure was collected from barns stored outside in piles. These were turned occasionally. Energy use for the farm was mainly in the form of diesel for machinery and electricity for the grain dryer. A summary of the energy use for the farm is included in table 5.6 and is used to calculate the baseline value.

Five scenarios were run through the *On-Farm Energy and Emissions* calculator, based on the current farm system with the addition of an anaerobic digester in accordance with the three staged construction process detailed above (section 5.2.3, figure 5.2). Each scenarios carbon equivalent emissions were calculated and compared with the baseline value. Scenarios 1 - 5 are outlined in table 5.2 and discussed in more detail below.

The farmer predominantly used energy in the form of diesel. Scenarios were therefore altered to produce vehicle gas through compressing the biogas, rather than electricity generation through a CHP unit. To use bio-methane or compressed biogas, the farmer would be required to modify his existing machinery or purchase natural gas/ bio-methane fuelled vehicles. The farmer was aware of and agreed that this would be a real consideration when looking into adopting anaerobic digesters. As the efficiency of these machines is dependent on what the farmer would choose, the amount of gas required to replace diesel use could not be calculated. Instead, the potential saving of what could be made from using the bio-methane, instead of the amount of energy generated, were deducted from the current diesel operations to give the total CO_2 equiv. emissions of the farm.

Table 5.2. Scenarios for mixed farm case study. Details on the energy use for each scenario is in table 5.6 and for the digester is in table 5.5

		Scenarios				
Details	Baseline	1	2	3	4	5
Using the farm's 580t of manure in anaerobic digester		X	X	X	X	X
Using biogas produced to power anaerobic digester			X	X		X
Converting excess biogas into vehicle fuel				X	X	X
Importing 200t of slurry as feedstock					X	X

1. Running the current farm system and incorporating the anaerobic digester as a method of manure management on the available feedstock only. This meant the biogas collected would not be used as an energy source, but would prevent the emissions normally released during farmyard manure (FYM) storage. Energy to power the anaerobic digester would be sourced from the Grid. Data were unavailable for emission savings from solid manure piles as a result of anaerobic digestion technology, although due to the reduction in carbon, there is likely to be a reduction in GHG emissions. As data are unavailable, for the sake of the model, a 50% reduction in emissions was suggested as used above with liquid slurry (Maranon *et al.* 2001)

2. Running the current farm system with an anaerobic digester fed on the currently available feedstock and using the gas collected to power a CHP unit.

3. As scenario two but with the surplus gas converted into vehicle gas, which could then be used as an alternative to imported diesel. Depending on the efficiency of the farmer's equipment, the calorific value for the methane to diesel would differ. Comparisons are made using a calorific value of what the biogas (5.96 kWh m^3) or bio-methane (9.96 kWh m^3) could generate, and diesel associated carbon emissions (2.63 kg CO_2 equiv. l^{-1}). (Values sourced from DEFRA 2007b, SKM Enviros 2011).

4. Using an anaerobic digester on the current feedstock, with all biogas generated to be used for gas upgrade for vehicle use. Heat and electricity required for the anaerobic digester and upgrading units would then be powered from external sources.

5. Importing an additional feedstock in the form of 200 t of dairy slurry per year at a cost of 57 l of diesel. Energy for the anaerobic digester and the gas upgrading unit would be powered by a CHP unit using biogas produced. Excess gas would be upgraded to use as vehicle fuel. A larger anaerobic digester would be required to accommodate the additional feedstock, and as a result, more energy would be required to operate it. This scenario would also hope to reduce the total emissions on the neighbouring farm.

5.3 Results

5.3.1 Dairy farm results

As a result of the differences between scenarios with additional feedstock; the digester size, daily total loading rate and energy requirements altered. These have been detailed in table 5.3 and were determined using the model.

Table 5.3. Details of the anaerobic digester required for each of dairy farm case study scenarios. Scenario's 1 - 3 only differ by how the biogas is used, and not on the system itself. Loading rate was kept at a constant 3 kg $m^{3\ -1}day^{-1}$ at an operating temperature of 35°C.

Scenario	AD* size (m^3)	Biogas produced (AD size ($m^3\ yr^{-1}$)	Retention time (days)	Electricity required (kWh yr^{-1})	Heat required (kWh yr^{-1})	Digestate (tonnes)	Loading rate (kg day^{-1})
Baseline	0	0	0	0	0	0	0
1-3	51	17147	30	5136	32669	539	138
4	99	39647	50	6052	44518	612	270

*AD = anaerobic digester

i) Dairy farm – Baseline values

A breakdown of the GHG emitting and the energy demanding sources for the farm are detailed below in table 5.4 There is uncertainty in the numbers due to their wide range and should therefore be used only as an indicative value, rather than an actual CO_2 equiv. figure for the farm. The energy use of the farm's machinery was supplied by the farmer and the CO_2 equiv. was calculated using the *On-Farm Energy and Emissions* calculator.

Cow enteric fermentation emissions were estimated to be between 71-123 kg CH_4 cow^{-1} yr^{-1}. This was based on a range of sources, including IPCC (See table 5.4 for full list). As the cows were organic, estimates of emissions may be slightly higher than for the average cow due to their high volume of forage (at least 60%) and low amount of concentrates (Lampkin *et al.* 2008, King *et al.* 2011).

The farmer currently stored his slurry in an open tank and applied using trail hose spreading. Estimates for these activities and the references for these values are included in table 5.4. The large range in the data values are due climatic, management, and experimental variations.

Table 5.4. Energy values and their carbon equivalent weights for farm activities calculated from a range of sources. To enable comparisons between the scenarios, an average and rounded value of 255 t CO_2 equiv. yr^{-1} was used.

Type	Source	Use	t CO_2 equiv. yr^{-1}	Sources of information
Electricity	Parlour	17,600 kWh	8.7- 8.8	Information from farmer and calculated by model
Electricity	Milk float	14,000 kWh	7.2-7.9	Information from farmer and calculated by model
Diesel	Crop Production	3,600l	12.7	Information from farmer and calculated by model
Emissions	Cows	70 dairy cows	124.6 - 215.3	(Amon *et al.* 2001, IPCC 2006, Johnson *et al.* 2007, Havlikova *et al.* 2008)
Emissions	Storage	Pit 560m^3 slurry	51.5 - 62.1	(Sommer *et al*. 2004, Amon *et al*. 2006, Clemens *et al*. 2006; Moitzi *et al*. 2007, Maranon *et al*. 2001)
Emissions	Spreading	Trail hose	0.13 - 0.65	(Clemens & Huschka, 2001, Pain 2003, Amon *et al*. 2006, Moitzi *et al*. 2007, Havlikova *et al*, 2008, Maranon *et al*. 2001)
Total		**Baseline value**	**204.2 - 307.3 t**	

ii) Dairy farm – Anaerobic digester scenarios

1. Running the current farm system, using an anaerobic digester as a method of manure management.

Due to the different manure treatment methods, emissions from slurry storage would reduce to between 143 - 239 t CO_2 equiv. An additional 37,805 kWh yr^{-1} of electricity sourced from external sources would be needed to power the anaerobic digester. The anaerobic digester's CO_2 footprint would be 10 t CO_2 equiv. yr^{-1}. In total the whole farming system would have a total carbon footprint of 182 - 279 t CO_2 equiv. This is an average difference of 25 t CO_2 equiv. below the baseline value.

2. *As above, but using the biogas collected in a CHP to heat and power the digester*.

All the GHG emissions would be the same as calculated for scenario one but with 100% of the anaerobic digester's heat and electricity requirement generated using the biogas produced. This would save 10 t CO_2 equiv. yr^{-1}. The farm's system would have a total carbon footprint of 172 – 269 t CO_2 equiv. This is an average difference of 36 t CO_2 equiv. below the baseline.

3. *As above but using surplus gas to power parlour and milk delivery float.*

The remaining electricity generated from scenario two could be used to power the parlour and the delivery vehicle, with 9,444 kWh remaining. This means there would be a decrease in 39,944 kWh being sourced externally and a saving of 16 t CO_2 equiv. The farm's total carbon footprint would therefore equate to 166 - 263 t CO_2 equiv. and mean a saving of 51 t CO_2 equiv. yr^{-1} compared with the baseline model.

4. *As above but with additional feedstock of 100 tonnes of imported broiler waste*.

By importing chicken manure from a farm 6 km away, the additional vehicle fuel would create 95 kg CO_2 equiv. Digester size would increase to 99 m^3 to accommodate the additional loading rate of 132 kg day^{-1} of material and the retention time would increase by 9 days. This would result in the digester needing an additional 916 kWh yr^{-1} of electricity and 5,588 kWh yr^{-1} of heat. In total, the carbon CO_2 equiv. for the anaerobic digester would be 14 t CO_2 equiv. As a result, the digester would generate in total 17,600 m^3 of methane, which if used in a CHP unit is 61,299 kWh yr^{-1}. After removing the energy required on the farm, there would be 23,389 kWh yr^{-1} of electricity remaining. The farm's total CO_2 equiv. emissions would therefore remain at 166 - 263 t CO_2 equiv. as the remaining electricity cannot be used on-site and would result in a saving of 48 t CO_2 equiv. yr^{-1} compared with the baseline model. To make further CO_2 equiv. savings, the remaining electricity must be used elsewhere or exported. For example by using it on a neighbours farm instead of them importing it from the Grid. If converted to electricity and used to replace fossil fuelled machines, an additional 12 t CO_2 equiv. could be saved. To generate figure 5.3, the value using the additional savings has been used for scenario 4.

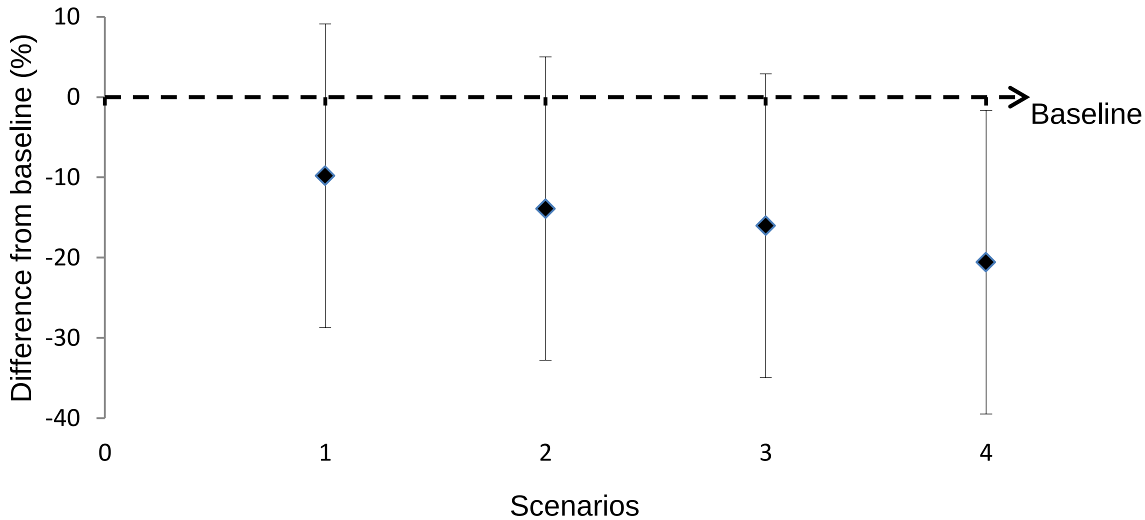


Figure 5.3. The percentage differences between the total CO_2 equiv. emissions for each scenario against the baseline (0%) for the dairy farm case study. Scenarios: 1. Using an AD unit for manure management only; 2. As (1) but using biogas in a CHP to power AD unit; 3. As (2) but using surplus gas to power farm operations; 4. As (3) but with 100t additional broiler waste imported. Bars represent range within the data sets.

A breakdown of all the sources of emissions within the dairy scenario is detailed in figure.5.4. From this it can be seen that enteric fermentation is the farm's largest contributor of CO_2 equiv. emissions.

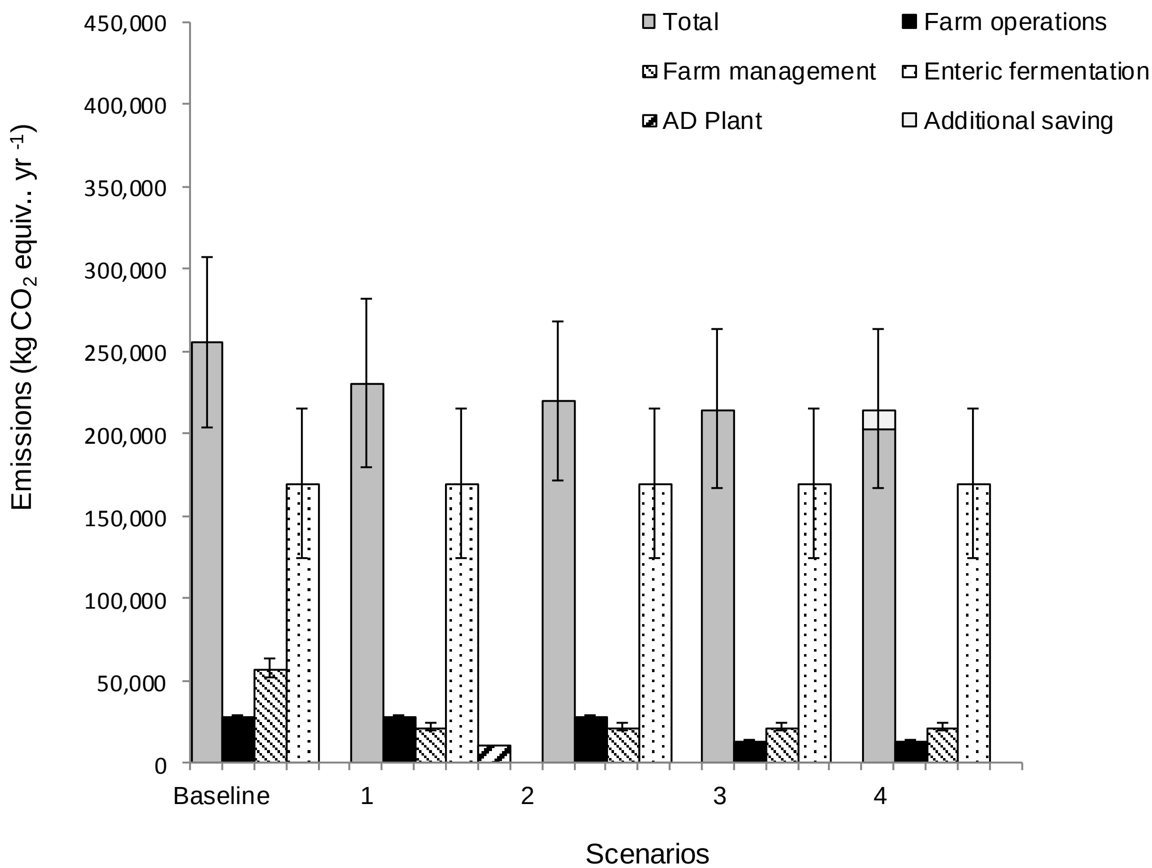


Figure 5.4. Dairy farm emissions without (baseline) and with anaerobic digester, the average of the emissions for each stage is plotted, with bars representing the range between the data values. Scenarios: 1. Using an AD unit for manure management only; 2. As (1) but using biogas in a CHP to power AD unit; 3. As (2) but using surplus gas to power farm operations; 4. As (3) but with 100 t additional broiler waste imported. Additional savings occur when excess biogas is exported/ used to replace other fossil fuel-derived energy from, for example, a neighbouring farm. A CO_2 equiv. saving is therefore made within the agricultural sector but not from the farm's own total saving.

5.3.2 Mixed farm results

As a result of the differences between scenarios with additional feedstock; the digester size, daily total loading rate and energy requirements altered. These have been detailed in table 5.5 and were determined using the *On-Farm Energy and Emissions* calculator.

Table 5.5. Digester details for each scenario run using a mixed farm as a case-study. Scenario's 1 - 3 only differ by how the biogas is used and not on the system itself. Loading rate was kept at a constant 3 kg $m^{3\ -1}day^{-1}$ at an operating temperature of 35°C.

Scenario	AD* size (m^3)	Biogas produced (AD size ($m^3\ yr^{-1}$)	Retention time (days)	Electricity required (kWh yr^{-1})	Heat required (kWh yr^{-1})	Digestate (tonnes)	Loading rate (kg day^{-1}
Baseline	0	0	0	0	0	0	0
1 – 4	117	37038	67	5361	45036	540	321
5	137	49705	58	7194	54130	725	375

*AD = Anaerobic digester

i) Mixed farm baseline values

A breakdown of the GHG emitting and the energy demanding sources for the farm are detailed below in table 5.6. The data vary less in their estimates than those found in the dairy scenario, but are still wide ranging, and should therefore be used only as an indicative value, rather than an actual CO_2 equiv. figure for the farm. The energy use of the farm's machinery was supplied by the farmer and the CO_2 equiv. was calculated using the *On-Farm Energy and Emissions* calculator.

Cow enteric fermentation emissions for beef cattle were estimated to be between 57 - 58 kg CH_4 cow^{-1} yr^{-1}. This was based on a range of sources, including IPCC (See table 5.6 for full list).

The farmer currently stored his manure in piles and applied it using a tractor and spiller. Estimates for these activities and the references for these values are included in table 5.6. The large data ranges are due climatic, management and experimental variations, with the lowest values considered being well aerated compost piles. Methane and nitrous oxide emission from the manures being spread were considered to be negligible as the majority of the gases would have been emitted during the storage process. For this analysis, they were therefore assumed to be zero. The emissions created from the machinery used to spread the manures are counted within the diesel use.

Table 5.6. The energy use and carbon equivalent emissions for each of the main operations on the mixed farm. To enable comparisons between the scenarios, the average and rounded value of 420 t CO_2 equiv. yr^{-1} is used.

Type	Source	Use	t CO_2 equiv. yr^{-1}	Sources of information
Electricity	Grain drying	20,000kwh	9.9	Information from farmer and calculated by model.
Diesel	Grain drying	10,000l	33.3	Information from farmer and calculated by model.
Diesel	Crop Production	20,000l	66.6	Information from farmer and calculated by model.
Emissions	Cows	200 beef cattle	285 – 290	(Amon *et al.* 2001, IPCC 2006, Johnson *et al.* 2007, Havlikova *et al.* 2008)
Emissions	Storage	Piles 580m^3 FYM	15 - 28.6	Amon et al., 2001; Flessa et al., 2002; Pattey et al., 2005.
Emissions	Spreading	Tractor and spiller	0	EPA, 1999.
Total		**Baseline value**	**410 – 428 t**	

ii) Mixed farm – Anaerobic digester scenarios

1. *Running the current farm system, using an anaerobic digester as a method of manure management*

Running the anaerobic digester as a manure management tool only would increase the farm's energy use by 50,397 kWh yr^{-1}, which is equivalent to 14 t CO_2 equiv. With the previous farm activities included with the anaerobic digester (crop production, machinery and grain drying) the farm's operations would equate to 124 t CO_2 equiv. yr^{-1}. The combined storage and spread of manure equated to 8 – 14 t CO_2 equiv. yr^{-1}. Therefore by incorporating an anaerobic digester for manure management purposes, the total carbon footprint would be 416 - 428 t CO_2 equiv. yr^{-1}.

2. *As above but using the collected gas as the energy source to heat and power the digester.*

In total, 22,223 m^3 of methane with a calorific value of 220,897 kWh could be produced. No imported electricity or heat would be needed to run the digester. The total carbon cost for the farm operations would therefore be equal to the baselines of 110 t CO_2 equiv. yr^{-1}. With the additional savings from the manure management of 8 - 14 t CO_2 equiv. yr^{-1}, the total farm emission would be around 402 - 414 t CO_2 equiv. yr^{-1}.

3. *As above with the surplus gas converted into bio-methane.*

The surplus gas would have a volume of 16,354 m^3 and a calorific value of 170,380 kWh. If this biogas was compressed and upgraded, further gas would be required to power the compressor and to upgrade. In total, there would be an increase in electricity consumption to 15,639 kWh and cost of 8 t CO_2 equiv. After this, there would be a remainder of 154,741 kWh or 15,567 m^3 of bio-methane. This does not take into account the additional heat that would be required as the current model sources this externally. On a direct calorific comparison, the 154,741 kWh could replace around 13,800 l of diesel oil, which is a saving of 46 t CO_2 equiv. The farm's total carbon footprint would then be 364 - 376 t CO_2 equiv. yr^{-1}. Additional carbon equivalent saving could be made if the excess bio-methane is used elsewhere, for example a neighbour's farm, although these savings would not be associated with the case study's farm directly.

4. *Using an anaerobic digester, with all biogas generated to be used for gas compression.*

By converting the biogas into bio-methane, 22,223 m^3 gas would be produced, with a carbon footprint saving of 52 t CO_2 equiv. if used to replace natural gas. On a calorific comparison, the bio-methane could replace 20,000 l of diesel oil, with a carbon saving of 67 t CO_2 equiv. This would mean all energy required for powering the anaerobic digester would need to be sourced from the Grid at a cost of 29 t CO_2 equiv. With the gas all compressed, the farm's total carbon footprint would be 380 - 392 t CO_2 equiv., depending on the efficiency and which forms of energy the farmer chose to replace with biogas. Additional savings could be made for the agricultural sector if the excess was exported onto another farm, reducing that farms use of fossil fuels.

5. *Using additional dairy slurry and CHP to power the anaerobic digester, with remaining gas being compressed.*

An additional 200 tonnes of slurry would increase the anaerobic digester's volume and energy requirements. The anaerobic digester would require 61,324 kWh of energy and create 18 t CO_2 equiv. yr^{-1}. The transport needed to import the slurry would create 190 kg CO_2 equiv. In total, the farm operations and waste management would equate to 419 - 431 t CO_2 equiv. By replacing the Grid sourced energy for energy generated in a CHP unit to power the digester, 17 t CO_2 equiv. could be saved. Again further savings could be made by exporting excess fuel and using it to replace other fossil fuel operations.

If the gas was upgraded and compressed, a further 21,000 kWh of electricity would be required, with additional heat being required from that generated in the CHP unit. In total, the anaerobic digester would create 4 t CO_2 equiv. from the imported energy for the heat. This would create 21,699 m^3 of compressed methane with a calorific value of 215,688 kWh. As a fuel, the biogas would have a calorific value equivalent to 22,398 l of diesel oil and could save 52 t CO_2 equiv., although this is dependent on the efficiency of the equipment used. With a CHP powering the anaerobic digester, using imported heat, and compressing the remaining gas into methane to replace diesel, the farms total carbon footprint would be 331 - 343 t CO_2 equiv. yr^{-1}.

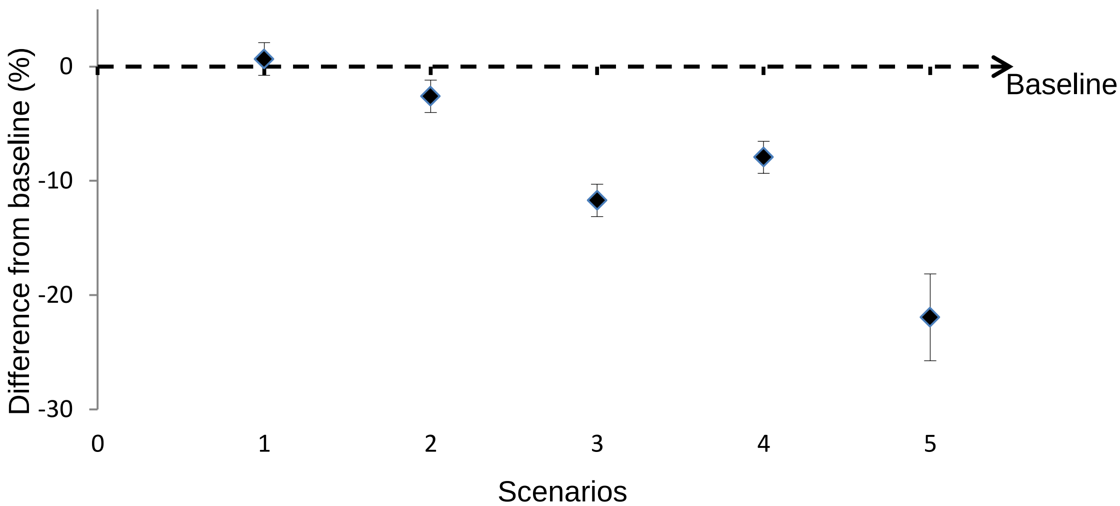


Figure 5.5. The percentage differences of total CO_2 equiv. emissions for each of the mixed farms scenario against the baseline (0%). Scenarios: 1. Using an AD unit for manure management only; 2. As (1) but using biogas in a CHP to power AD unit; 3. As (2) but surplus gas converted into bio-methane; 4. As (1) but with all gas being converted into bio-methane; 5. A (3) with an additional 200 t slurry imported. Bars represent the range within the data.

A breakdown of all the sources of GHG emissions within the mixed farm scenario is detailed in figure 5.6. Enteric fermentation is the largest contributor towards the farm's CO_2 equiv. emissions. This is followed by the farm operations that are currently mainly diesel powered.

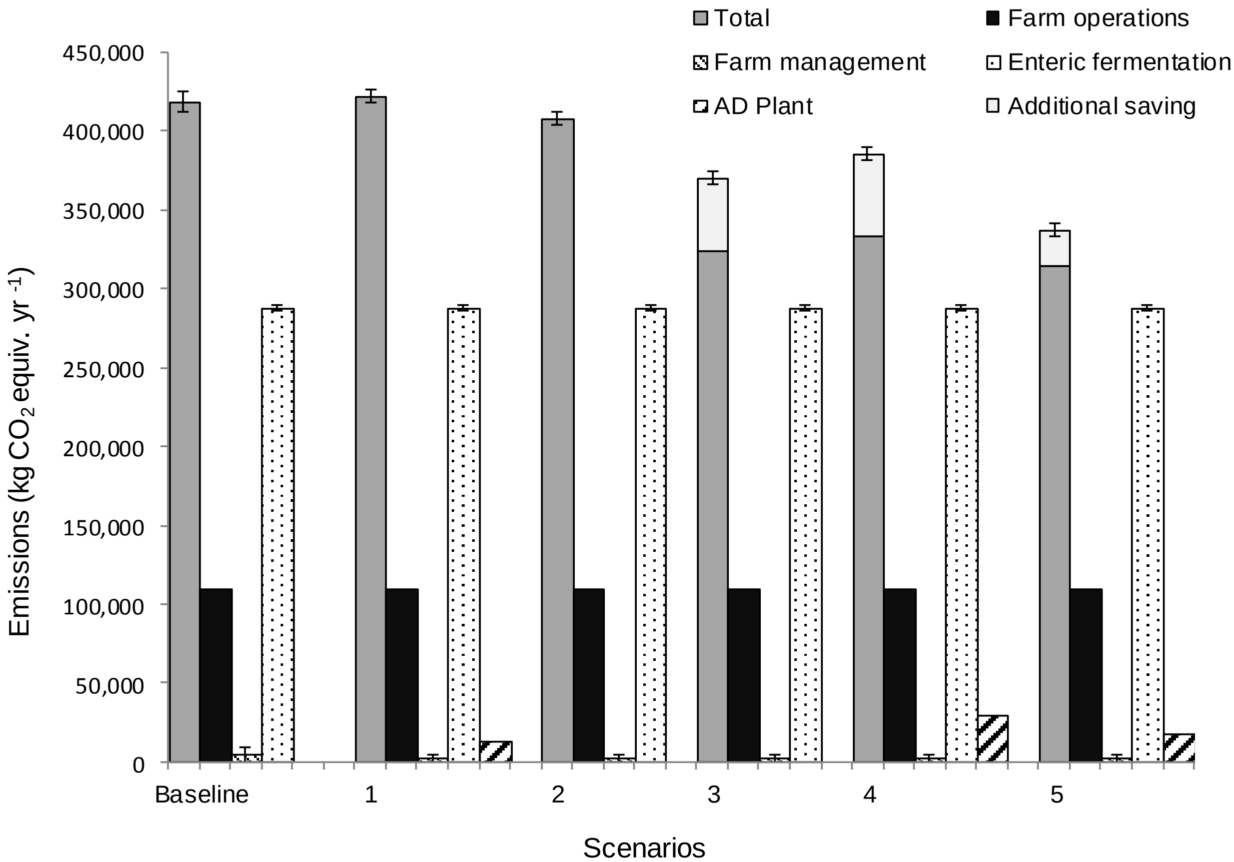


Figure 5.6. The carbon equivalent emissions for the mixed farm case study without (baseline) and with an anaerobic digester. Scenarios: 1. Using an AD unit for manure management only; 2. As (1) but using biogas in a CHP to power AD unit; 3. As (2) but surplus gas converted into bio-methane; 4. As (1) but with all gas being converted into bio-methane; 5. A (3) with an additional 200 t slurry imported. Bars represent the range within the data values. Ranges are much smaller than those within the dairy farm scenarios due to less variation within data sets used from the literature. Additional savings occur when excess biogas is exported/ used to replace other fossil fuel-derived energy from, for example, a neighbouring farm. A CO_2 equiv. saving is therefore made within the agricultural sector but not from the farm's own total saving.

5.4 Discussion

Using an anaerobic digester to treat farm organic matter can reduce GHG emissions (Amon *et al.* 2001, Amon *et al.* 2006, Clemens *et al.* 2006, Moitzi *et al.* 2007). Here, two case study farms were modelled to explore the potential savings an anaerobic digester could have. The amount by which the farms' GHG emissions were reduced were case specific and depended on how the farmer used the biogas produced. The results from this chapter express only the trends in GHG emissions for each of the case studies, rather than accurate GHG emission values.

5.4.1 The impact of an anaerobic digester on a farm's carbon footprint.

Using the anaerobic digester solely for manure management increased both of the farms' total GHG emissions. Although an anaerobic digester could capture gases released from inefficiently managed compost piles (Clemens & Ahlgrimm 2001, Sandars *et al.* 2003), the energy required to power the anaerobic digester would need to be sourced from external sources. For both case studies, the emissions produced from powering the anaerobic digester would be greater than the savings made from the improved manure management. To overcome this, the products of the anaerobic digester must be used, for example, to replace fossil fuel-derived energy.

No additional GHG emissions would be created if the energy required to power the anaerobic digester did not outweigh the total amount of energy produced. Within the scope of these case studies, the anaerobic digester would be self-sustaining and carbon neutral (see section 5.2.1 for model boundaries). In reality, the initial GHG emissions cost for building and starting up the anaerobic digester would not be recovered if no additional savings were made (excluded from analysis). Also, if the gas production dropped, or the system needed to be re-started (for maintenance purposes for example), the system would no longer be carbon neutral as an external source of energy would be required to restart the system. To ensure an anaerobic digester does not create additional GHG emissions, the biogas needs to have an additional use to powering itself alone. It would be of interest to farmers, for example organic farmers, to maximise their GHG emission savings within their farming systems for environmental reasons.

Using biogas to replace fossil fuel use in vehicles and electricity generation could reduce a farm's total GHG emissions and make the farm system more energy sustainable. It would also make finances on the farm more predictable by reducing outgoing costs (not considering the original establishment costs for the anaerobic digester), and making it less susceptible to market energy price fluctuations.

i) Comparisons of the case studies' potential carbon footprint savings

From the absolute GHG emission values, the mixed farm had a greater reduction in the total carbon equivalent savings from its baseline. This comparison of absolute GHG emission savings between the two farms is strongly affected by the greater size of the mixed farm (six times the acreage and nearly 3 times the number of livestock). To adjust for this, the percentage savings from the baseline of each farm were calculated. Using only the farms' available feedstock and the energy produced for on-farm operations (dairy: scenario 3 and mixed farm: scenario 3), the average potential GHG emission saving for the dairy farm was 16.5% and for the mixed farm was 11.7%, compared to their baselines. This meant both farm types could reduce their total GHG emissions by using an anaerobic digester.

Although the dairy farm saved 4.2% more than the mixed farm against its baseline value, a comparison of the range of percentage savings for each scenario for each case study (see figures 5.3 and 5.5) demonstrates much greater uncertainty about the outcome for the dairy farm. Notwithstanding the wide variation in scores (±19% for each scenario), the dairy farm does demonstrate progressively improving average savings throughout the scenarios tested.

5.4.2 The influence of an anaerobic digester on a farm's energy self-sufficiency

The equipment to convert biogas into either bio-methane or electricity is costly (See appendix 7 for example costing). It is likely therefore farmers will invest in only one option. If a farmer is powering their anaerobic digester with a CHP unit, they are likely to use the CHP unit to power other farm operations too. Exporting excess electricity could generate profits. For farmers interested in bio-methane, the cost of purchasing a CHP unit to power the anaerobic digester alone may not be worthwhile. Here, sourcing electricity from the Grid, and using a boiler to provide the anaerobic digester with heat may be the best option in terms of energy efficiency. A financial comparison has not been made within this report due to its complexity and rapid fluctuations (Anderson *et al.* 2013).

To make their investment worthwhile, both farmers were interested in maximising biogas production and wanted to convert the gas into an energy source they used most frequently. The dairy farmer mainly used electricity to power his parlour and dairy delivery vehicle. The mixed farmer mainly used diesel to power vehicles and understood that his machinery would need to be modified if he was to use bio-methane. Both of the farmers' decisions fitted in with the typical organic farming ethos as discussed in chapter four in that they wanted to reduce their environmental impact, rather than exporting all their energy produced to maximise profits.

The available volume of slurry on the dairy farm produced enough biogas to power the farm's operations and the anaerobic digester (scenario 3). Additional feedstock was required on the mixed farm to make the farm self-sufficient in energy. Even with the additional cow slurry available, the anaerobic digester would not have been able to produce enough biogas to power itself and the farms operations. The conversion of biogas into bio-methane to replace diesel has previously been shown not to be as efficient as other bio-fuel alternatives (Fredriksson *et al.* 2006). Fredriksson *et al*. (2006) found using bio-methane would be problematic as the required infrastructure was not easily available, specifically for small scale systems. It would therefore have a high GHG emissions compared to alternative options such as rape methyl ester.

There are various options available for farmers to generate electricity through renewable energy technologies, including solar, wind and hydro power generation. These options also require little disruption to the current practices on the farm. They may also have a higher energy efficiency than electricity generated from biogas (SKM Enviros 2011). In comparison, there are only a few renewable energy enterprises that can generate fuel or gas like products, and those that can, often require crop and land use changes (Fredriksson *et al.* 2006, Dijkman & Benders 2010, Stephenson *et al.* 2010, van Dam *et al.* 2010). Their efficiency calculated through life-cycle analysis also varies greatly. For example, bio-ethanol produced from wheat or maize was not considered to be sustainable if grown in temperate climates (de Vries *et al.* 2010) and biodiesel from oil seed rape grown in the UK had very little impact on its CO_2 equiv. emissions (Stephenson *et al.*

2008). These, as well as other biofuel crops, can also create other environmental problems due to the high nitrogen, water and energy requirements involved in crop production (Pimentel 2003, Kim & Dale 2005, Hahn & Cecot 2009, de Vries *et al.* 2010). These in turn may affect market prices of energy and food due to miscalculated subsidies (Pimentel 2003, Hahn & Cecot 2009). Biogas could therefore produce a market in fuel production with the potential to avoid environmental and ethical issues created from growing energy crops (Fredriksson *et al.* 2006).

5.4.3 Suitability of anaerobic digesters for dairy and mixed farms

Although a wider range of results was obtained for each scenario in the dairy farm study, this type of farming appears more likely to benefit from the installation of an anaerobic digester. This is because dairy farmers have a high volume and regularity of digester feedstock (slurry) and easier re-use of the energy outputs as electric power. Financially, large dairy farms were considered to be the best farm type option too (Anderson *et al*. 2013). Dairy farms were considered to be better farm type for an anaerobic digester for a range of reasons discussed in chapter four.

Anaerobic digestion can help slurry management by reducing the total organic content of the material, while increasing the inorganic nitrogen content of the material. This results in a lower total volume of material being spread and less diesel being used to power the spreaders. Although a high volume of slurry is available on the dairy farm, the efficiency of biogas produced from slurry is lower than in other organic materials (NNFCC 2011). Based on a weight comparison of feedstock efficiency, slurry had a lower potential energy yield than FYM. This is because FYM contains crop residues which, compared with slurry alone, has a higher biogas potential. For example, one tonne of cattle slurry produces only 15 - 25 m^3 of biogas, while grass silage and maize silage produce 160 - 200 m^3 and 200 - 220 m^3 of biogas respectively (NNFCC 2011). Faeces and crop material together therefore will have a higher biogas potential than faeces alone.

Mixed farmers may have access to more than just FYM as modelled here. They may, for example, have access to more and more varied crop residues than dairy farms. By using waste organic materials such as straw, root crop tops and crop wastes such as potatoes damaged during harvesting, mixed farms can greatly increase their digester feedstock availability and gas production (NNFCC 2011). The nutrients lost within the crop material can also be recovered in the digestate fertiliser (Banks *et al*. 2011a). Removing crop residuals from the field may disrupt other ecological and environmental functions (Natural England 2010). For example, leaving fields exposed can lead to soil erosion and leaching of nutrients (Thomsen *et al.* 2010, Kassam & Brammer 2013). Replacing the once residual crop with a covering of digestate may help to prevent erosion, and could replace organic matter. The potential for using stubble as a feedstock should be considered carefully by those who leave stubble in their fields as part of their Environmental Stewardship Schemes (Natural England 2010). This is because stubble provides habitat for in-field nesting birds such as corn-bunting (*Emberiza calandra*) and skylarks (*Alauda arvensis*), and a food source for birds during the winter and spring such as linnet (*Carduelis cannabina*) and grey partridge (*Perdix perdix*) (Natural England 2010) and its removal will hinder recovery effects of these species. Exposed fields may also have implications for weed management and earthworm populations, as discussed in chapter 2.

These models were based on a single year’s production, so while slurry is being produced throughout the year, the mixed farmer may have feedstock sporadically, in particular, after harvest or when seasonally clearing sheds. This means the stored material will either be fermenting during storage and release methane emissions or be composted to reduce the emissions of methane. Both of these processes will result in a reduction in the biogas potential of the stored feedstock.

5.4.4 The limitations of this chapter and of an anaerobic digester’s ability to reduce farm carbon footprints.

i) Limitations of the chapter

The scenario options discussed within this chapter were limited by the constraints of the *On-Farm Energy and Emissions* calculator and may not represent the most practical use of the biogas. For example, the mixed farm could have used the biogas in a boiler to heat the anaerobic digester, as this was the largest energy running cost, and imported the electricity from the Grid. The remaining gas could then be used as a fuel source, without the need for a CHP unit at all. In the dairy farm case, the heat generated from the CHP unit could be used within the parlour for heating, rather than converting biogas into electricity through a CHP unit. Both of these options would have fitted with the farm’s current operations better and may have resulted in a lower carbon footprint than modelled here.

A direct calorific value was used to estimate the amount of biogas required to replace the diesel used on the farm. The efficiency of the conversion from biogas to diesel was unknown for each piece of machinery and therefore not taken into account. It is likely a higher volume of biogas would be required to power the diesel machinery than through a direct calorific value as used here. The GHG emissions from converting biogas to diesel are therefore likely to be higher than estimated here.

ii) Limitations of anaerobic digesters

Organic farming does not permit the use of synthetic chemicals (Lampkin *et al.* 2008). If they were to use their organic material in an anaerobic digester, they would need to use the digestate as their fertiliser substitute. This has been discussed in greater depth in chapters two and three. Using digestate instead of composted materials may emit lower GHGs (as modelled within this chapter), although these savings would be small. By replacing synthetic fertilisers with digestate, the high emissions associated with their production and transportation could be avoided (Lal 2004, Berglund & Börjesson 2006). Again, the total savings made would be farm case dependent.

Anaerobic digester technology does not tackle the largest existing sources of GHG emissions within agriculture, for example enteric fermentation, which is the largest source of methane emissions in livestock farming, accounting for around 80% of methane (Amon *et al.* 2001).

Overall, anaerobic digesters can be used as tools for reducing GHG emissions. This is by capturing methane released and replacing fossil fuel-derived energy. Due to the limitations of anaerobic digesters they are not a solution to reduce agricultural emissions but may be used as part of a holistic approach and in conjunction with other GHG emission reducing technologies. In particular, methods that reduce emissions from enteric fermentation will have the largest impact on reducing emissions within UK agriculture.

Prior to investing in an anaerobic digester, farmers may wish to consider alternative methods of reducing GHG emissions and increasing their sustainability by adopting energy efficient technologies such as using compact fluorescent lighting, improving insulation, and using energy efficient fans, heaters and cooling systems (Carbon Trust 2006). Also, many other renewable energy technologies offer energy generation without requiring feedstock, which may be particularly of benefit to farms without organic material available to them, for example solar or wind.

5.5 Conclusions

Because the data values used to calculate the farms' carbon footprints are very approximate estimates, only general trends can be seen, rather than actual calculations of the farms' potential GHG emission savings. The main findings from the chapter are;

- Using an anaerobic digester solely for manure management would not reduce GHG emissions below the levels produced by the anaerobic digester, and therefore would not be an environmentally worthwhile enterprise.

- An anaerobic digester could reduce a farm's carbon footprint if the biogas that is produced is used to power the digester and additional operations.

- Using the biogas to replace fossil fuel-derived energy was the most efficient method of reducing the case study farms' carbon footprints.

- Further GHG emissions associated with agriculture could be reduced if other wastes are imported from neighbouring farms, although to what extent would be case dependent.

- From these case studies, dairy farms could prove more suited to the use of anaerobic digesters. This is due to their high volume of material available and their high electricity use. This finding compliments the findings in chapter four.

- Enteric fermentation is the largest source of GHG emissions on both of the farm case studies. Research efforts therefore should continue to look into methods to reduce enteric fermentation.

- Farmers should consider investing in energy saving methods before considering building an anaerobic digester.

Chapter 6

General Discussion

6.1 General discussion

The main aim of this thesis was to assess to what degree anaerobic digesters are suitable for organic farms. To achieve a thorough investigation, a multidisciplinary approach was taken using methods from the environmental, ecological and social sciences. Each of these disciplines had its own interpretation of what was meant by "suitable" and as a result, each offered an alternative perspective to address the main aim. By drawing together the findings from each chapter, an overall conclusion as to whether anaerobic digesters are suitable for organic farms can be made.

Using the IFOAM definition of organic farming, the key areas include; functioning in an holistic way, *relying on ecological processes, biodiversity and cycles*, avoiding the *use of input with adverse effects* and using techniques that *benefit the shared environment* (IFOAM 2008). A measure of suitability can therefore be derived from examining the areas where conflicts and compliments are found between the definition for organic farming and the implication of using an anaerobic digester.

6.1.1 Holistic farming- *relying on ecological processes, biodiversity and cycles.*

A key element of organic farming is farming holistically. This type of farming aims to minimise the input of materials, while reusing and recycling the produced products. By doing this, organic farmers aim to manage their farms in a closed system by using natural cycles (Lampkin *et al.* 2008). Within this thesis two areas, where anaerobic digesters could help an organic farm become more holistic, were examined. These were a) the concept of using digestate to replace nutrients, thus completing the nutrient cycle using soil biota and b) using self-produced energy so as to reduce or remove the need for externally sourced energy.

i) Nutrient cycles

Organic farmers strive towards making the nutrient cycle on their farms holistic. Currently organic farmers replace lost nutrients back onto their field by recycling organic matter produced on the farm. Chemical fertilisers do not require soil biota to release their nutrients as they can feed the crops directly. As organic farmers cannot use chemical fertilisers, they must rely on the organic fertilisers they use being broken down and the nutrients released by soil biota. When using an anaerobic digester on an organic farm, it is therefore important that the digestate still functions in the same way as other organic fertilisers and does not miss out the stage involving soil fauna. Failing to feed and support soil biodiversity could result in a loss of biodiversity and therefore could have consequences on crop production (Brussaard *et al.* 2007).

Biological experiments using earthworms were designed around the concept of the anaerobic digester being based on a dairy farm. This was partly due to information found in the literature, and partly from the development from the results each of the chapters. During the interviews (chapter four), farmers emphasised the importance of using products that supported soil biota. For this thesis, earthworms were considered a good indicator of soil health and were used as a test species. In addition, the questionnaire respondents and interview participants (chapter four) considered dairy farms to be the most likely enterprise to consider an anaerobic digester. This meant that slurry was used as a fertiliser comparison and was the main feedstock to create the digestate. The earthworms' responses were monitored using field (chapter two) and laboratory (chapter three) trials. Together the results from chapters two and three highlighted the potential effects digestate can have on different species.

Organic farmers try to encourage earthworms into their fields for their positive influence on soil fertility (see introduction section 1.3.1.1.ii for more on earthworm functioning groups) (Edwards & Lofty 1972, Mader *et al.* 2002). Ideally anecic species are encouraged because of their larger size and ability to consume greater quantities of organic matter. This enables them to incorporate these larger quantities to greater depths compared to other species (Neilson & Boag 2003). It was a member of the anecic functioning group that was negatively affected by the application of digestate in chapter three. Replacing slurry with digestate could therefore have a negative effect on soil fertility and therefore overall productivity. By disrupting one earthworm group, there could be knock-on effects with the whole soil community, and therefore impact biotic and abiotic elements of the habitat (Syers & Springett 1984, Sheehan *et al.* 2007). For example, disrupting deep burrowing species may increase the difficulty for deep root growth of some crops. This was seen in field trials on cereal roots that use channels in the soil created by earthworms (Edwards & Lofty 1980). Population effects on earthworm species were potentially seen within the field trials where the size distribution of earthworms differed between the treatment plots. Careful consideration of which type of land the digestate should be applied could help reduce the risk of disruption. Compost earthworms, for example, chose to inhabit soil treated with digestate compared to slurry, so using digestate to fertilise agricultural enterprises where high compost-like materials are used, such as horticulture, may be more beneficial than using digestate to fertiliser crop lands. Further research into how digestate can be used is currently being conducted by WRAP through the Digestate and Compost in Agriculture project (WRAP project reference OMK001-001)

Although digestate at high concentration appears to be harmful, there are some characteristics which can reduce its harmful effects. Exposing digestate to soil for one week prior to experimentation appeared to suppress its harmful effects on earthworms. This harmful effect may be associated with volatile chemicals which are released which exposed to the air, for example ammonia emissions (Spurgeon & Weeks 1998, Van Gestel & Weeks 2004). Aerating the digestate before application may reduce the harmful effects it can have on earthworms and this suggests an area for engineers to develop equipment that can aerate digestate without releasing harmful emissions. The digestate used within this thesis was produced using a single anaerobic digester, however digestate created using a double or multiple stage tank process or storing digestate under cover may show different results (Amon *et al.* 2006, Ward *et al.* 2008). Ammonia emission are high after spreading digestate compared with slurry and so low emission application techniques are recommended when spreading (Seadi & Lukehurst 2012). This could include injection application (Clemens & Ahlgrimm 2001), however by using this method exposure is more direct to soil biota and earthworms and therefore could impact on populations and soil communities.

Nitrogen Vulnerable Zone limits

During a number of the laboratory experiments, the concentration value 170 kg N ha^{-1} was used as an experimental application. Although this is the maximum nitrogen value organic farmers are permitted to apply to their land, the results from chapter three suggest that applications higher than this can have a negative impact on earthworms. The same was seen when using slurry as a fertiliser, although not to the same extent as with digestate. Currently, the DEFRA guidelines *Protecting our Soil Water, and Air* (2009d) suggest that conventional farmers are able to apply an average of 250 kg N ha^{-1} across their fields. As

170kg N ha^{-1} is the average maximum permitted across the whole organic farm, areas may receive more than this; in particular areas growing nutritionally demanding crops. These crops, for example maize, can also be used to produce high energy biogas (NNFCC 2011). An organic farmer therefore, growing maize to feed their digester may be required to apply more digestate to maize fields to boost the yield. Although during the season that it is fertilised with digestate the yield of the crop may not be affected, as organic fields are in rotation the higher application of digestate may well affect the established earthworm population which will be required to maintain soil fertility for later seasons. This could therefore have an impact on the yields of other crops being grown in following years. According to the interview participants from chapter four, they rarely grew energy demanding crops or applied all of the allotted nitrogen to their fields, thus reducing the risk of the soil biota being affected. This therefore may not be a current issue, but with the increasing uptake of anaerobic digesters, it could be an issue in the future. The application of digestate should therefore be monitored for each field to ensure levels are not exceeded.

Farmers using chemical fertilisers may rely on earthworms less to maintain the fertility of their soils. Non- organic farmers and those farmers who are not located on an NVZ are permitted to apply up to 250 kg N ha^{-1} across their farm. This means that not only can they dispose of more digestate per hectare, they are also less concerned with detrimental effects digestate may have on their earthworm populations.

Overall, digestate offers organic farmers an alternative fertiliser option to slurry without the fear of additional effects on soil biota when used within existing limits and practices. The results from this thesis highlight a potential risk for some farmers who both rely on soil biota to break down organic matter and release nutrients, and that use more than 170kg N ha^{-1} to fertilise high nutritionally demanding crops.

ii) Energy self-sufficiency

The prospect of an organic farmer making their farm energetically self-sufficient using an anaerobic digester was very attractive to the respondents of the surveys in chapter 4, although many did not believe it could work on their own farms. The farmers interviewed in chapter four who believed that an anaerobic digester could work on their farm talked about importing additional material to feed their digester. The purpose of chapter five therefore was to look into whether two model farms could generate enough energy to meet their personal needs from only their own available organic material. For the dairy farm case study, the energy was used as electricity, and was able to power the parlour, milk float and the anaerobic digester from the slurry alone. This supported the conclusion from chapter 4 that anaerobic digesters seem to be best suited to dairy enterprises. The mixed farm case study failed to be energy self-sufficient when powering the digester using only its own organic material. To generate enough energy to power the farm, the mixed farmer would also need to grow additional crops or import organic material from an external source. Within this case study, the energy was used as bio-methane, with the intention of replacing diesel which was currently being used. Previous studies have shown poor efficiency in converting biogas into vehicle fuel compared with other methods of generating renewable vehicle fuels (Hansson *et al*. 2007, Freddriksson *et al*. 2006). Generating electricity therefore seems to be the best use of the biogas that is produced using feedstock created on the farm for farm-scale anaerobic digesters.

Growing additional crops raised ethical concerns within the interviews and this issue was mentioned in some of the responses to the questionnaires. There were also concerns that the land used to grow crops to feed anaerobic digesters might not be considered organic (Soil Association, 2009), and that land within the Energy Crops Scheme cannot be used within the Organic Entry Level Stewardship (Natural England 2010). The idea of importing waste, for example food waste, created debate from the interviewees. This was mainly due to the fear of potential GM contamination. Currently, the Soil Association do allow imports onto farms, but only with their permission (Soil Association 2008). The interviewed farmers from chapter 4 were also concerned that importing materials would stop the farm from being a holistic system and therefore conflict with IFOAM's definition of organic farming.

Overall, the perception of achieving energy self-sufficiency on an organic farm, using an anaerobic digester, was more difficult than alternative options for generating renewable energy. From the data analysed in chapter 5, self-sufficiency is possible on certain organic farms. The organic farmers interviewed were more likely to consider other renewable energy options than anaerobic digesters due to financial issues and fears that not enough energy would be produced to make it worthwhile. This was despite being told about farms that current ran anaerobic digesters in the UK and abroad.

6.2.2 Avoid the *use of input with adverse effects*.

According to IFOAM's definition of organic farming, farmers should avoid the use of inputs that will have adverse effects. The use of fossil fuel-derived energy has an adverse effect on the environment (Johnson *et al.* 2007), and is used on organic farms to generate energy in a number of forms. Organic farmers can reduce their dependence on external energy sources by generating and utilising their own energy. Reducing external inputs by replacing them with renewable energy sources should therefore be a key component of organic practices. Despite this, there is limited emphasis on promoting the use of renewable energies within organic standards from an international level (IFOAM 2008).

Organic farmers are unlikely to object to further promotion of farm based renewable energy generation. From the farmers interviewed, half were already generating renewable energy, most felt that as an organic farmer it was their role to do so and all showed an interest in generating renewable energy. Within Austria, 23% of biogas plants are run by organic farmers, while only 9% of Austrian farmers are organic (Walla & Scheneeberger 2003). Further evidence of organic farmers supporting renewable energy comes from the selection of case studies used in the RASE, "A Review of Anaerobic Digester Plants in the UK", where 3 of the 9 farms with anaerobic digesters were organic farms (Bywater 2011). Due to the rarity of organic farms in the UK (around 4.3% of agricultural land is organic (DEFRA 2008b), this is a much higher proportion of organic farmers represented than would be expected by chance. On an individual basis, many organic farmers have chosen, or are considering investing in renewable energies, but to further encourage renewable energy generation on all organic farms, it is up to the certifiers to review their guidelines and support renewable energy technologies.

The aim of the International Federation of Organic Agriculture Movements (IFOAM) is to lead, unite and assist the organic movement across the world. National certifiers therefore must firstly comply with IFOAM's regulations before imposing their own. Currently IFOAM believe organic farming should reduce the use of non-renewable energy by avoiding agro-chemicals, but rarely promote on their website the use of renewable energies (IFOAM 2006). As a result, other organic bodies do not need to encourage renewable energy generation. For example The Organic Food Federation, a UK certifier, currently state within their standards that "organic farming should primarily rely on renewable resources within locally organised agricultural systems in order to minimise the use of non-renewable resources" (Organic Food Federation 2008, section 3.1.8), however they do not specifically mention energy generation as an example of this, or promote renewable energy in any other way.

Some certifying bodies, for example Organic Farmers and Growers, are making positive moves towards promoting renewable energies. Their 2006 standards recommended the use of anaerobic digestion as a method of managing waste, reducing emissions and producing a utilisable biogas (Organic Farmers and Growers 2006, Section 7.13.05). Furthermore, they now support the use of anaerobic digesters on farms by conducting the inspection and certification services of the Biofertiliser certification schemes in accordance with the PAS110 and the Anaerobic Digestion Quality Protocol (see introduction section 1.2.2.i for further details). Of the farmers interviewed, only one farmer mentioned this scheme suggesting that little is currently known about it. Another major advance in encouraging renewable energies on organic farms is within the Soil Association. Prior to April 2008, the Soil Association exhibited similar ambiguity with regards to renewable energy as IFOAM, and only mention using anaerobic digestion as a method for managing waste (Soil Association 2009b, section 4.7.14). Since then, they have released a briefing paper on anaerobic digesters, advertising their support for the technology, and in the 16.6 version of their standards, they intend to introduce targets for renewable energy generation, with the intention of making them a requirement by 2016 (Version 16.6 section 5.2.4, April 2012). As the Soil Association is the largest organic certifier within the UK, this additional standard could be seen as a major advance in encouraging farms to consider renewable energy generation and will result in a large number of farmers investing in it.

So far, the drive towards adopting renewable energies has being led by individual farmers rather than being driven by the organic international bodies. National certifiers are beginning to make a positive move towards encouraging renewables, but, as none of the farmers participating in this thesis mentioned the new standard being introduced by the Soil Association, evidence of a change in attitude appears to be slow. National organic certifiers are making information available to support technologies, and in particular anaerobic digesters, although there was little evidence from the interviews that the information was reaching the farmers. By publishing information, certifiers are showing more support towards the importance of renewable technologies within sustainable farming, although this information too needs to be received by the farmers themselves.

As yet; there is little influential pressure at an international level to promote renewable technologies. To promote organic farming and its original principles, a change in attitudes towards renewable energy needs to be made at all levels of organic agriculture. Overall, organic farming priorities need to be re-evaluated to better address the current world issues of energy security and environmental sustainability, if it is to stay true to its original values.

6.2.3 Techniques that *benefit the shared environment.*

Organic farmers are encouraged to use techniques that benefit the environment through their own behaviours and in accordance to organic standards. Anaerobic digesters can offer organic farmers a method that can benefit the environment in at least two ways. Firstly a) it can offer organic farmers an alternative method to treat their waste and as a result, create an improved fertiliser compared to slurry. Secondly b) anaerobic digesters can be used to generate renewable energy which can reduce the GHG emissions associated with agriculture.

i) Digestate as an alternative fertiliser

There are multiple benefits to be derived from replacing existing organic fertilisers with digestate. The most important benefit is likely to be the availability of nutrients. The nutrients within digestate are often in a more accessible form for plants to utilise, enabling farmers to fertilise crops accurately and rapidly (Seadi & Lukehurst 2012). The total nitrogen for example, remains the same within the digestate as in the feedstock; however the amount of ammonical nitrogen increases in digestate (Goberna *et al.* 2011). The results from using digestate as a fertiliser in chapter two showed that digestate significantly increased total grass yield. As nutrients are available in their inorganic forms, digestate should be applied when plant uptake is at its maximum (Goberna *et al.* 2011). Careful application timing should prevent or minimise run off and reduce the risk of water pollution. As the digestate can be separated between its liquid and solid fraction, these two fractions can be utilised depending on the field’s nutritional requirements. For example, the solids of digestate contain high amounts of phosphate and organic matter and can be used as a soil conditioner. The liquid faction can be used as a fertiliser with a reduced risk that excess phosphate will leach into waterways and cause eutrophication (Seadi & Lukehurst 2012). Therefore digestate can be used to better target the needs of the field than slurry.

There are also application benefits to using digestate. Digestate can be spread using the same methods as used for spreading slurries. Due to the lower organic matter content in digestate compared to slurry with the same total N content, a lower volume needs to be applied and so there is less to transport around. This means that less fuel is needed to apply the same concentration of nitrogen. Also, as grass yield was found to be higher, less land is required to grow the same yield. Farmers that use digestate on their fields have also claimed that their grass was greener than previously (personal communication, Walford College). Work into the effect digestate has on Italian Ryegrass is currently being conducted by WRAP (WRAP project reference OMK001-001). Caution is required however as high levels of volatile ammonia are released when digestate is spread and so appropriate methods should be used depending on the field type in order to minimise air pollution (Wulf *et al.* 2002a).

Anaerobic digesters can offer farmers an alternative method to storing and treating organic matter. Some of the farmers interviewed in chapter four said that composting was their current method of treating organic matter. They appeared to understand the importance of this, and the environmental issues related. Despite this, a number of the farmers admitted to not turning their piles as frequently as they should. Failure to turn piles can result in increased emission and poor breakdown of materials (Clemens & Ahlgrimm 2001, Sandars *et al*. 2003) and have an impact on a farm's total emission. Anaerobic digestion therefore offers them a technology whereby turning is not required and the material is housed in an air tight container. This in turn was seen to reduce the amount of GHG emission from farm case studies examined in chapter five.

Additional benefits of using digestate include potential reductions in odour (Hansen et al., 2004); pathogens (Paavola & Rintala 2008, Goberna *et al.* 2011) and surviving weed seeds (Engeli *et al.* 1993), compared with using slurry (Yiridoe *et al.* 2009). Digestate was also found, in chapter two, to help prevent the emergence of weeds, yet not facilitate the growth of thistles.

ii) Collection of Greenhouse Gases and farm carbon footprints

Anaerobic digesters can be used as a method to prevent GHG emissions into the environment. By preventing GHG emissions being released into the atmosphere and using the methane emissions as an energy source, farmers can reduce their farms' carbon footprints. According to the questionnaires, organic farmers were more interested in reducing their carbon footprints than conventional farmers. The interviewed organic farmers also believed they were more environmentally aware and considerate than conventional farmers and may therefore be interested in technologies such as anaerobic digesters, which benefit the environment. From the findings of chapter five, anaerobic digesters can be used to reduce the emissions associated with agriculture, both directly from the management of manures and indirectly by the replacement of fossil fuel sourced energy with renewably generated energy. With a conventional farm, indirect GHG emissions are much higher than those of an organic farm (Dalgaard *et al*. 2001) due to the use of external chemicals; this therefore can have additional savings than those described by the farms used in chapter five.

From the two case studies in chapter five, the highest percentage carbon footprint saving was seen on the dairy farm. This saving was partly due to the high efficiency of converting biogas into electricity and partly due to the electricity generated being utilised on the farm. The conversion of biogas into bio-methane, for vehicle use, was less efficient but still made GHG emission savings. One option for a conventional farmer to reduce the farm's carbon footprint is to generate electricity from the biogas and then "carbon trade" it with vehicle fuel. This may be more difficult to justify for an organic farmer as according to the farmers interviewed, they wanted to generate renewable energy to reduce their own impact on the environment directly. Participating in carbon trading would also reduce the holistic approach of organic farms and, although the farmer would be reducing the total GHG emissions into the environment they would end up being responsible for generating more GHG emissions on their farm. The main increase in GHG emissions from this would be from powering the anaerobic digester itself, as seen in chapter five. The idea of carbon trading therefore does not fit within the definition of organic farming, despite having shared goals to reduce negative impacts on the environment.

The largest source of GHG emissions from both the farm systems were from enteric fermentation of the livestock. It therefore makes sense to invest in technologies and research that may help reduce this source of GHG emissions. Unfortunately, some of these options conflict with organic farming practices. For example, organic cattle feeds must contain at least 60% roughage, fodder or silage and must be low in concentrates (Soil Association 2009). High fibre diets result in high enteric fermentation which helps break down the plant materials, resulting in high levels of methane being released (Clemens & Ahlgrimm 2001, King *et al*. 2011). It is therefore important to assess which farming techniques create the biggest net impact for organic farmers; using an anaerobic digester where suitable may be one option.

6.2.4 Where are anaerobic digesters best suited?

In conclusion, the environmental benefits an anaerobic digester can offer theoretically fit well within the principles of organic farming; however the benefits an anaerobic digester can deliver for organic farms may be limited. Certain farms appear to be better suited for anaerobic digesters but this can depend on the farmer's measure of suitability. For example, whether to use it as a tool to generate energy for use on the farm to make is self-sustainable or to use as a tool to generate energy to sell. Taking into consideration the IFOAM's organic definition, dairy farms appear to be the most suitable organic farming enterprise to use an anaerobic digester. This has been evident throughout this thesis in a number of the chapters and within the literature;

1. Organic farmers grow grass for grazing. Here digestate used as a fertiliser was found to increase total biomass of Italian ryegrass (chapter two).
2. If used within suggested limits digestate does not disrupt earthworm populations in the soil and may even promote population numbers in certain species (chapter three).
3. Dairy farmers were considered to be the most likely enterprise to invest in an anaerobic digester (chapter four).

4. The organic farmers primarily wanted to use the energy generated onsite, reducing their use of fossil fuelled derived energy (chapter four and five).

5. Organic dairy farmers have readily available feedstock in the form of slurry (chapter four & five).

6. Dairy farmers are likely to convert the biogas into heat and electricity, which is a more efficient use of the biogas than converting it to vehicle fuel (chapter five).

It was also evident during the thesis research that anaerobic digesters may be better suited on conventional farms. This was partially the case if the main aims of anaerobic digesters are to generate finances or make substantial contributions towards government targets associated with reducing GHG emissions and increasing renewable energy use. As organic farms have strict boundaries in which they must operate to remain certified, farming systems with more lenient boundaries appear to be more able to achieve these aims. Non-organic farmers may therefore be more suitable to use an anaerobic digester for a number of reasons identified within the thesis and from the literature;

1. Digestate also may potentially reduce weed germination which could reduce the amount of herbicides they require (Chapter two,(Yiridoe *et al.* 2009))

2. Conventional farmers can dispose of the digestate easier, either off-site or onto fields without being penalised by organic regulations (WRAP 2008, Soil Association 2009, DEFRA 2009d, chapter 4).

3. Conventional farmers can import feedstock with high methane potentials more easily, for example food waste (DEFRA 2010a, WRAP 2008, Soil Association 2008).

4. Conventional farmers are able to grow maize more easily, a very suitable crop to feed anaerobic digesters (Banks *et al.* 2007; chapter 4, Lampkin *et al.* 2008) Chapter four).

5. Conventional farmers can grow energy crops or crops specifically for an anaerobic digester without risking subsidies or disrupting established rotations (DEFRA 2010a, DECC 2009b, Soil Association 2009)

6. Conventional farmers can charge gate fees for imported food wastes to increase profits.

7. Due to more feedstock being available to conventional farmers, more energy can be produced and the excess can be sold (Banks *et al.* 2007, Raven & Gregersen 2007).

8. Any replacement of chemical fertilisers with digestate can help conventional farmers to reduce their total GHG emissions (Clemens & Ahlgrimm 2001, IPCC 2001, Yiridoe *et al.* 2009).

9. Neighbouring conventional farms could consider using a shared anaerobic digester to reduce costs without the fear of high transportation costs or fear of contaminants. (Soil Association 2009, (Ma *et al.* 2005, Soil Association 2008, Soil Association 2009b, Yiridoe *et al.* 2009, Klavon *et al.* 2013)

Overall, organic farms can potentially utilise anaerobic digesters successfully without conflicting with their standards. They are limited as to what extent they can use an anaerobic digester to contribute towards government targets for reducing emissions and increasing renewable energy generation, and are limited in the amount of energy and therefore profits that they can generate. Using an anaerobic digester can offer them some soil fertility options, for example, when separated; the two fractions of digestate can be used according to the needs of the field. Conventional farmers face fewer regulations which allow them to maximise the use of an anaerobic digester on their farm to treat existing and alternative waste. They are therefore able to contribute to national targets, both on a farm scale by reducing GHG emissions and using renewable energy and also externally from the farm, being available to treat alternative wastes and use digestate to their benefit thus reducing waste to landfill and generating excess renewable energy.

References

AD-Nett, (2005a) *The European Anaerobic Digestion Network* [online]. [Accessed 2011].

AD-Nett, (2005b) *Farm Biogas Plants in EU.* [online]. http://www.adnett.org/ [Accessed 2010].

Amon, B., Amon, T., Boxberger, J. & Alt, C., (2001). Emissions of NH3, N2O and CH4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). *Nutrient Cycling in Agroecosystems,* **60** (1), 103-113

Amon, B., Amon, T., Kryvoruchko, V., Machmuller, A., Hopfner-Sixt, K., Bodiroza, V., Hrbek, R., Friedel, J., Potsch, E., Wagentristl, H., Schreiner, M. & Zollitsch, W., (2007). Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. *Bioresource Technology,* **98** (17), 3204-3212

Amon, B., Kryvoruchko, V., Amon, T. & Zechmeister-Boltenstern, S., (2006). Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agriculture Ecosystems & Environment,* **112** (2-3), 153-162

Anderson, R.C., Hilborn, D. & Weersink, A., (2013). An economic and functional tool for assessing the financial feasibility of farm-based anaerobic digesters. *Renewable Energy,* **51**, 85-92

Arncken, C.M., Mader, P., Mayer, J. & Weibel, F.P., (2012). Sensory, yield and quality differences between organically and conventionally grown winter wheat. *Journal of the Science of Food and Agriculture,* **92** (14), 2819-2825

Azeez, M.G. & Hewlett, K., (2008) The Comparative Energy Efficiency of Organic Farming. Poster at: Cultivating the Future Based on Science. *2nd Conference of the International Society of Organic Agriculture Research ISOFAR.* Modena, Italy.

Baghai, T.C., Eser, D. & Moller, H.J., (2008). Effects of different antidepressant treatments on the core of depression. *Dialogues Clin Neurosci,* **10** (3), 309-20

Bailey, J.A., Gordon, R., Burton, D. & Yiridoe, E.K., (2008). Factors which influence Nova Scotia farmers in implementing energy efficiency and renewable energy measures. *Energy,* **33** (9), 1369-1377

Balfour, L.E.B., (1943) *The Living Soil and the Haughley Experiment*: Universe Books.

Banks, C., (2009) Optimising Anaerobic Digestion. presented at Reading University: University of Southampton.

Banks, C., Salter, A., Swinbank, A., Tranter, R., Jones, P., Poppy, G.M., Clarke, D. & Muskolus, A., (2011a) *Integrated systems for farm diversification into energy production by anaerobic digestion: implications for rural development, land use & the environment.* Southampton, RES-229-25-0022.

Banks, C.J., Chesshire, M., Heaven, S. & Arnold, R., (2011b). Anaerobic digestion of source-segregated domestic food waste: Performance assessment by mass and energy balance. *Bioresource Technology,* **102** (2), 612-620

Banks, C.J., Salter, A.M. & Chesshire, M., (2007). Potential of anaerobic digestion for mitigation of greenhouse gas emissions and production of renewable energy from agriculture: barriers and incentives to widespread adoption in Europe. *Water Science and Technology,* **55** (10), 165-173

Beddington, J., (2010). Food security: contributions from science to a new and greener revolution. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **365** (1537), 61-71

Beedell, J. & Rehman, T., (2000). Using social-psychology models to understand farmers' conservation behaviour. *Journal of Rural Studies,* **16** (1), 117-127

Berg, B.L., (2007) *Qualitative Research Methods for the Social Sciences,* 6th ed. London: Pearson Education, Inc.

Berglund, M. & Börjesson, P., (2006). Assessment of energy performance in the life-cycle of biogas production. *Biomass and Bioenergy,* **30** (3), 254-266

Bermejo, G., Ellmer, B.J. & Kruck, S., (2010) *Use of Dry and Wet Digestates from Biogas Plants as Fertilizer in Plant Production.* Berlin.

Bertora, C., Alluvione, F., Zavattaro, L., Willem van Groenigen, J., vVelthof, G. & Grignani, C., (2008). Pig Slurry treatment modifies slurry composition, N_2O, and CO_2 emissions after soil Incorporation. *Soil Biology & Biochemistry,* **40**, 1999-2006

Bilalis, D., Sidiras, N., Economou, G. & Vakali, C., (2003). Effect of different levels of wheat straw soil surface coverage on weed flora in Vicia faba crops. *Journal of Agronomy and Crop Science,* **189** (4), 233-241

Blackshaw, R.E., Molnar, L.J. & Larney, F.J., (2005). Fertilizer, manure and compost effects on weed growth and competition with winter wheat in western Canada. *Crop Protection,* **24** (11), 971-980

Blake, F., (1990) *Organic Farming and Growing,* revised edition ed.: The Crowood Press.

Blunden, G., Moran, W. & Bradly, A., (1997). 'Archaic' relations of production in modern agricultural systems: the example of sharemilking in New Zealand. *Environment and Planning A,* **29** (10), 1759-1776

Bonkowski, M., Griffiths, B.S. & Ritz, K., (2000). Food preferences of earthworms for soil fungi. *Pedobiologia,* **44** (6), 666-676

Booth, L.H., Hodge, S. & O'Halloran, K., (2001). Use of biomarkers in earthworms to detect use and abuse of field applications of a model organophosphate pesticide. *Bulletin of Environmental Contamination and Toxicology,* **67** (5), 633-640

Boscolo, A., Mangiavacchi, C., Drius, F., Rongione, F., Pavan, P. & Cecchi, F., (1993). Fuzzy Control of an Anaerobic Digester for the Treatment of the Organic Fraction of Municipal Solid-Waste (Msw). *Water Science and Technology*, **27** (2), 57-68

Bowler, I., Clark, G., Crockett, A., Ilbery, B. & Shaw, A., (1996). The development of alternative farm enterprises: A study of family labour farms in the northern Pennines of England. *Journal of Rural Studies,* **12** (3), 285-295

Braber, K., (1995). Anaerobic digestion of municipal solid waste: A modern waste disposal option on the verge of breakthrough. *Biomass & Bioenergy,* **9** (1-5), 365-376

Brauckmann, H.-J. & Broll, G., (2007) Auswirkkungen der Ausbringen von Garresten aus Biogasanlagen auf Regenwurmer. *Deutsche Bodenkundliche Gesellscheft.* 747-748.

Britto, D.T. & Kronzucker, H.J., (2002). NH4+ toxicity in higher plants: a critical review. *Journal of Plant Physiology,* **159** (6), 567-584

Brussaard, L., de Ruiter, P.C. & Brown, G.G., (2007). Soil biodiversity for agricultural sustainability. *Agriculture Ecosystems & Environment,* **121** (3), 233-244

Burton, R.J.F. & Wilson, G.A., (1999). The Yellow Pages as a sampling frame for farm surveys: Assessing potential bias in agri-environmental research. *Journal of Rural Studies,* **15** (1), 91-102

Butler, A., (2010) The good, the bad and the ugly: lessons from biogas plant planning applications. *ROOTS.* Plumpton College, East Sussex: RICS.
Bywater, A., (2011) *A review of Anaerobic Digester Plants in the UK.* Kenilworth.
Carbon Footprint, (2013) *Carbon Offsets, Offsetting and Neutrality* [online]. http://www.carbonfootprint.com/carbonoffset.html [Accessed 2013].
Carbon Trust, (2006) *Agriculture and Horticulture sector overview.* London.
Carbon Trust, (2011) *Carbon Footprinting* [online]. http://www.carbontrust.co.uk/cut-carbon-reduce-costs/calculate/carbon-footprinting/Pages/carbon-footprinting.aspx [Accessed 2011].
Carruthers, S.P. & Jones, M.R., (1983) *Biofuel production strategies for UK agriculture* Reading: Centre for Agricultural Stragy.
CEC, (2007) *Biofuels Progress Report.* Brussels.
Chan, K.-Y. & Munro, K., (2001). Evaluating mustard extracts for earthworm sampling. *Pedobiologia*, **45** (3), 272-278
Clark, J., (2009). Entrepreneurship and diversification on English farms: Identifying business enterprise characteristics and change processes. *Entrepreneurship and Regional Development*, **21** (2), 213-236
Clemens, J. & Ahlgrimm, H.J., (2001). Greenhouse gases from animal husbandry: mitigation options. *Nutrient Cycling in Agroecosystems*, **60** (1-3), 287-300
Clemens, J., Trimborn, M., Weiland, P. & Amon, B., (2006). Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agriculture Ecosystems & Environment*, **112** (2-3), 171-177
Coenraads, R., Reece, G., Voogt, M., Ragwitz, M., Held, A., Resch, G., Faber, T., Haas, R., Konstantinaviciute, I., Krivošík, J. & Chadim, T., (2008) *Promotion and Growth of Renewable Energy Sources and Systems.* Utrecht, TREN/D1/42-2005/S07.56988.
Committee on Climate Change, (2008) *Building a low-carbon economy – The UK's contribution to tackling climate change.* Norwich: TSO.
Cordell, D., Drangert, J.-O. & White, S., (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, **19** (2), 292-305
Cotton, D.C.F. & Curry, J.P., (1980). The Response of Earthworm Populations (Oligochaeta, Lumbricidae) to High Applications of Pig Slurry. *Pedobiologia*, **20** (3), 189-196
Crush, J.R., Cosgrove, G.P. & Brougham, R.W., (1982). The Effect of Nitrogen-Fertilizer on Clover Nitrogen-Fixation in an Intensively Grazed Manawatu Pasture. *New Zealand Journal of Experimental Agriculture*, **10** (4), 395-399
Curll, M.L., Wilkins, R.J., Snaydon, R.W. & Shanmugalingam, V.S., (1985). The Effects of Stocking Rate and Nitrogen-Fertilizer on a Perennial Ryegrass White Clover Sward .1. Sward and Sheep Performance. *Grass and Forage Science*, **40** (2), 129-140
Curry, J.P., Byrne, D. & Schmidt, O., (2002). Intensive cultivation can drastically reduce earthworm populations in arable land. *European Journal of Soil Biology*, **38** (2), 127-130
Dalgaard, T., Halberg, N. & Porter, J.R., (2001). A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agriculture Ecosystems & Environment*, **87** (1), 51-65

Darnhofer, I., Schneeberger, W. & Freyer, B., (2005). Converting or not converting to organic farming in Austria: Farmer types and their rationale. *Agriculture and Human Values*, **22** (1), 39-52

Davis, J. & Haglund, C., (1999) *Life Cycle Inventory (LCI) of Fertiliser Production. Fertiliser Products Used in Sweden and Western Europe.* Chalmers University of Technology.

De Lorenzo, M.E., Scott, G.I. & Ross, P.E., (2001). Toxicity of pesticides to aquatic microorganisms: a review. *Environmental Toxicology and Chemistry,* **20**, 84-98

de Vries, S.C., van de Ven, G.W.J., van Ittersum, M.K. & Giller, K.E., (2010). Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. *Biomass and Bioenergy,* **34** (5), 588-601

Dear, M., (1992). Understanding and Overcoming the NIMBY Syndrome. *Journal of the American Planning Association*, **58** (3), 288-300

DECC, (2009a) National Renewable Energy Action Plan for the United Kingdom. London.

DECC, (2009b) Renewable Obligations Order. *In* Change., D.o.E.C. London.

DECC, (2009c) The UK Renewable Energy Stratagy. *In* Change., D.o.E.C. Surrey: TSO.

DECC, (2010) *UK Climate change sustainable development indicator: 2009 Greenhouse Gas Emissions, Provisional Figures and 2008 Greenhouse Gas Emissions, Final Figures by Fuel Type and End-user.* . London.

DECC, (2011a) *Agriculture- GHG Inventory summary Factsheet.* London.

DECC, (2011b) *Feed-in tarrif scheme: summary of responses to the fast-track Consultation and Government Response.* London.

DECC, (2011c) *UK Climate Change Sustainable Development indicator: 2010 Greenhouse Gas Emissions, Provisional Figures and 2009 Greenhouse Gas Emissions, Final Figures by Fuel Type and End-user.* London.

DECC, (2011d) *UK Energy in Brief 2011.* London.

DEFRA, (2007a) *Barriers to Farm Diversification- Report of the joint industry.* London: Copyright, C.

DEFRA, (2007b) *Guidelines to DEFRA's GHG conversion factors for company reporting.* London: Copyright, C.

DEFRA, (2008a) Guidance for Farmers in Nitrate Vulnerable Zones: Field application of manufactured nitrogen fertilisers. *In* Department for Environment, F.a.R.A. London: Defra Publications.

DEFRA, (2008b) *Organic statistics.* York.

DEFRA, (2009a) *Agriculture in the United Kingdom.* London.

DEFRA, (2009b) *Developing an Implementation Plan for Anaerobic Digestion.* London.

DEFRA, (2009c) *Protecting our Water, Soil and Air. A Code of Good Agricultural Practice for farmers, growers and land managers.* Surrey: Office, T.S.

DEFRA, (2009d) *Protecting our Water, Soil and Air: A Code of Good Agricultural Practice for farmers, growers and land managers.* Norwich: TSO.

DEFRA, (2010a) Accelerating the Uptake of Anaerobic Digestion in England: An Implementation Plan. *In* DEFRA. Crown Copyright.

DEFRA, (2010b) *Agriculture in the United Kingdom.* York.

DEFRA, (2011a) *Agricultural Statistics and Climate Change.* London: Copyright, C.

DEFRA, (2011b) *Implementation of the Nitrates Directive in England 2013-2016* [online]. http://www.defra.gov.uk/consult/2011/12/20/nitrates-directive/ [Accessed 2012].
Deike, S., Pallutt, B. & Christen, O., (2008). Investigations on the energy efficiency of organic and integrated farming with specific emphasis on pesticide use intensity. *European Journal of Agronomy*, **28** (3), 461-470
Dench, S., Iphofen, R. & Huws, U., (2004) *An EU Code of Ethics for Socio-Economic Research.* Brighton.
Dent, D., (1995) *Intergrated Pest Management*, 1st ed. London: Chapman & Hall.
Didden, W.A.M., (2001). Earthworm communities in grasslands and horticultural soils. *Biology and Fertility of Soils*, **33** (2), 111-117
Dijkman, T.J. & Benders, R.M.J., (2010). Comparison of renewable fuels based on their land use using energy densities. *Renewable & Sustainable Energy Reviews*, **14** (9), 3148-3155
Dominguez, J., Bohlen, P.J. & Parmelee, R.W., (2004). Earthworms increase nitrogen leaching to greater soil depths in row crop agroecosystems. *Ecosystems*, **7** (6), 672-685
EA, (2011) *Anaerobic Digestion (Biogas)* [online]. Environment Agency. Available from: http://www.environment-agency.gov.uk/business/sectors/32601.aspx [Accessed
EC, (1991) The Nitrates Directive. *In* Commission, E. Brussels: European Economics Council.
EC, (2002) *6th European Action Programme* [online]. European Commission. Available from: http://ec.europa.eu/environment/newprg/archives/intro.htm [Accessed 2010].
The Renewables Directive 2009.
Edmeades, D.C., (2003). The long-term effects of manures and fertilisers on soil productivity and quality: a review. *Nutrient Cycling in Agroecosystems*, **66** (2), 165-180
Edwards, C.A., Arancon, N.Q., Vasko-Bennett, M., Little, B. & Askar, A., (2009). The relative toxicity of metaldehyde and iron phosphate-based molluscicides to earthworms. *Crop Protection*, **28** (4), 289-294
Edwards, C.A. & Lofty, J.R., (1972) *Biology of Earthworms* London: Chapman and Hall LTD.
Edwards, C.A. & Lofty, J.R., (1980). Effects of Earthworm Inoculation Upon the Root-Growth of Direct Drilled Cereals. *Journal of Applied Ecology*, **17** (3), 533-543
Edwards, C.A. & Lofty, J.R., (1982). Nitrogenous Fertilizers and Earthworm Populations in Agricultural Soils. *Soil Biology & Biochemistry*, **14** (5), 515-521
Edwards, P.J. & Brown, S.M., (1982). Use of Grassland Plots to Study the Effect of Pesticides on Earthworms. *Pedobiologia*, **24** (3), 145-150
EEA, (2009) *What is Waste* [online]. European Environmental Agency. Available from: http://scp.eionet.europa.eu/themes/waste [Accessed
Elsayed, M.A., Matthews, R. & Mortimer, N.D., (2003) *Carbon and Energy Balances for a Range of Biofuels Options.* Sheffield.
Engeli, H., Edelmann, W., Fuchs, J. & Rottermann, K., (1993). Survival of Plant-Pathogens and Weed Seeds during Anaerobic-Digestion. *Water Science and Technology*, **27** (2), 69-76
EPA, (1999) Livestock Manure Management.

Ernst, G., Muller, A., Gohler, H. & Emmerling, C., (2008a). C and N turnover of fermented residues from biogas plants in soil in the presence of three different earthworm species (Lumbricus terrestris, Aporrectodea longa, Aporrectodea caliginosa). *Soil Biology & Biochemistry*, **40** (6), 1413-1420

Ernst, G., Müller, A., Göhler, H. & Emmerling, C., (2008b). C and N turnover of fermented residues from biogas plants in soil in the presence of three different earthworm species (Lumbricus terrestris, Aporrectodea longa, Aporrectodea caliginosa). *Soil Biology and Biochemistry*, **40** (6), 1413-1420

EurObserv-ER, (2012) *Biogas Barometer* [online]. http://www.eurobserv-er.org/pdf/baro212biogas.pdf [Accessed 2013].

Fairweather, J.R., (1999). Understanding how farmers choose between organic and conventional production: Results from New Zealand and policy implications. *Agriculture and Human Values*, **16** (1), 51-63

Falconer, K., (2000). Farm-level constraints on agri-environmental scheme participation: a transactional perspective. *Journal of Rural Studies*, **16** (3), 379-394

Fan, Z.L. & Gerowitt, B., (2002) Effects of light, nitrogen and propagative sources on Creeping thistle. *The Annual Conference on Tropical and Subtropical Agricultural and Natural Resource Management.* Kassel-Witzenhausen.

Farooqui, T., (2013). A potential link among biogenic amines-based pesticides, learning and memory, and colony collapse disorder: A unique hypothesis. *Neurochemistry International*, **62** (1), 122-136

Ferrer, I., Gamiz, M., Almeida, M. & Ruiz, A., (2009). Pilot project of biogas production from pig manure and urine mixture at ambient temperature in Ventanilla (Lima, Peru) *Waste Management*, **29** (1), 168-173

Firestone, J., Kempton, W., Lilley, M.B. & Samoteskul, K., (2012). Public acceptance of offshore wind power across regions and through time. *Journal of Environmental Planning and Management*, **55** (10), 1369-1386

Fitzpatrick, L.C., Muratti-Ortiz, J.F., Venables, B.J. & Goven, A.J., (1996). Comparative Toxicity in Earthworms *Eisenia fetida* and *Lumbricus terrestris* Exposed to Cadmium Nitrate Using Artificial Soil and Filter Paper Protocols. *Bulletin of Environmental Contamination and Toxicology*, **57** (1), 63-68

Fowler, J., Cohen, L. & Jarvis, P., (1998) *Practical Statistics for Field Biology*: John Wiley and Sons Ltd.

Fredriksson, H., Baky, A., Bernesson, S., Nordberg, A., Noren, O. & Hansson, P.A., (2006). Use of on-farm produced biofuels on organic farms - Evaluation of energy balances and environmental loads for three possible fuels. *Agricultural Systems*, **89** (1), 184-203

Frund, H.C., Egbert, E. & Dumbeck, G., (2004). Spatial distribution of earthworms [Lumbricidae] in recultivated soils of the Rhenish lignite-mining area, Germany. *Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde*, **167** (4), 494-502

Garcia, M., Rombke, J., de Brito, M.T. & Scheffczyk, A., (2008). Effects of three pesticides on the avoidance behavior of earthworms in laboratory tests performed under temperate and tropical conditions. *Environmental Pollution*, **153** (2), 450-456

Garcia, S.G., (2005) *Farm scale anaerobic digestion intergrated in an organic farming system*. Swedish University of Agricultural Sciences.

Gerin, P.A., Vliegen, F. & Jossart, J.-M., (2008). Energy and CO2 balance of maize and grass as energy crops for anaerobic digestion. *Bioresource Technology,* **99** (7), 2620-2627

Gillham, B., (2005) *Research Interviewing the range of techniques,* 1st ed. Maidenhead: Open University Press.

Girling, R.D., Ennis, D., Dillon, A.B. & Griffin, C.T., (2010). The lethal and sub-lethal consequences of entomopathogenic nematode infestation and exposure for adult pine weevils, Hylobius abietis (Coleoptera: Curculionidae). *Journal of Invertebrate Pathology,* **104** (3), 195-202

Goberna, M., Podmirseg, S.M., Waldhuber, S., Knapp, B.A., Garcia, C. & Insam, H., (2011). Pathogenic bacteria and mineral N in soils following the land spreading of biogas digestates and fresh manure. *Applied Soil Ecology,* **49**, 18-25

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. & Toulmin, C., (2010). Food Security: The Challenge of Feeding 9 Billion People. *Science,* **327** (5967), 812-818

Gorton, M., Douarin, E., Davidova, S. & Latruffe, L., (2008). Attitudes to agricultural policy and farming futures in the context of the 2003 CAP reform: A comparison of farmers in selected established and new Member States. *Journal of Rural Studies,* **24** (3), 322-336

Gunn, A., (1992). The Use of Mustard to Estimate Earthworm Populations. *Pedobiologia,* **36** (2), 65-67

Hahn, R. & Cecot, C., (2009). The benefits and costs of ethanol: an evaluation of the government's analysis. *Journal of Regulatory Economics,* **35** (3), 275-295

Hall, G.M. & Howe, J., (2012). Energy from waste and the food processing industry. *Process Safety and Environmental Protection,* **90** (3), 203-212

Hansson, H., Ferguson, R. & Olofsson, C., (2010). Understanding the diversification and specialization of farm businesses. *Agricultural and Food Science,* **19** (4), 269-283

Hansson, P.A., Baky, A., Ahlgren, S., Bernesson, S., Nordberg, A., Noren, O. & Pettersson, O., (2007). Self-sufficiency of motor fuels on organic farms - Evaluation of systems based on fuels produced in industrial-scale plants. *Agricultural Systems,* **94** (3), 704-714

Harrison, G.P., Eltham, D.C. & Allen, S.J., (2008). Change in public attitudes towards a Cornish wind farm: Implications for planning. *Energy Policy,* **36** (1), 23-33

Havlikova, M., Kroeze, C. & Huijbregts, M.A.J., (2008). Environmental and health impact by dairy cattle livestock and manure management in the Czech Republic. *Science of the Total Environment,* **396** (2-3), 121-131

Heenan, D.P., Chan, K.Y. & Knight, P.G., (2004). Long-term impact of rotation, tillage and stubble management on the loss of soil organic carbon and nitrogen from a Chromic Luvisol. *Soil & Tillage Research,* **76** (1), 59-68

Hobbs, P.J., Johnson, R. & Chadwick, D., (1999). A novel technique to determine organic processes in pig wastes. *Journal of the Science of Food and Agriculture,* **79** (2), 199-205

Hogetsu, A., Ishikawa, T., Yoshikawa, M., Tanabe, T., Yudate, S. & Sawada, J., (1992). High-Rate Anaerobic-Digestion of Wool Scouring Waste-Water in a Digester Combined with Membrane-Filter. *Water Science and Technology,* **25** (7), 341-350

Holloway, L.E. & Ilbery, B.W., (1996). Farmers' attitudes towards environmental change, particularly global warming, and the adjustment of crop mix and farm management. *Applied Geography*, **16** (2), 159-171

Holm-Nielsen, J.B., Al Seadi, T. & Oleskowicz-Popiel, P., (2009). The future of anaerobic digestion and biogas utilization. *Bioresource Technology,* **100** (22), 5478-5484

Hund-Rinke, K. & Kordel, W., (2003). Underlying issues in bioaccessibility and bioavailability: experimental methods. *Ecotoxicology and Environmental Safety,* **56** (1), 52-62

Hund-Rinke, K., Lindemann, M. & Simon, M., (2005). Experiences with novel approaches in earthworm testing alternatives. *Journal of Soils and Sediments,* **5** (4), 233-239

Hund-Rinke, K. & Wiechering, H., (2001). Earthworm Avoidance Test for Soil Assessments. *Journal of Soils and Sediments,* **1** (1), 15-20

IFOAM, (2006) The IFOAM Norms for Organic Production and Processing. Germany: IFOAM.

IFOAM, (2008) *Definition of Organic Agriculture* [online]. World Board. Available from: http://www.ifoam.org/growing_organic/definitions/doa/index.html [Accessed 2008].

Igoni, A.H., Ayotamuno, J.M., Eze, C.L., Ogaji, S.O.T. & Probert, M.E., (2008). Designs of anaerobic digesters for producing biogas from municipal solid-waste. *Applied Energy,* **85**, 430-438

Ilbery, B. & Saxena, G., (2009). Evaluating 'best practice' in integrated rural tourism: case examples from the England-Wales border region. *Environment and Planning A,* **41** (9), 2248-2266

Ilbery, B.W., (1991). Farm Diversification as an Adjustment Strategy on the Urban Fringe of the West Midlands. *Journal of Rural Studies,* **7** (3), 207-218

Ilbery, B.W. & Bowler, I.R., (1993). The Farm Diversification Grant Scheme - Adoption and Nonadoption in England and Wales. *Environment and Planning C-Government and Policy,* **11** (2), 161-170

IPCC, (2001) *Climate Change 2001: Mitigation*: Change, I.P.o.C.

IPCC, (2006) *IPCC Guidelines for National Greenhouse Gas Inventories.* Hayama, Japan.

ISO, (1993) Soil Quailty- effects of Pollutants on Earthworms (*Eisenia fetida*) Institute of Standardisation Organisation.

Soil Quality, Part 4. Biological Methods, Subsection 4.2.3: Guidance on the Determination of Effects in Field Situations. 2000.

Soil Quality -- Avoidance test for determining the quality of soils and effects of chemicals on behaviour -- Part 1: Test with earthworms (*Eisenia fetida and Eisenia andrei*) 2008.

Jansen, J.L., Nyberg, U., Aspegren, H. & Andersson, B., (1993). Handling of Anaerobic Digester Supernatant Combined with Full Nitrogen Removal. *Water Science and Technology*, **27** (5-6), 391-403

Johnson, J.M.F., Franzluebbers, A.J., Weyers, S.L. & Reicosky, D.C., (2007). Agricultural opportunities to mitigate greenhouse gas emissions. *Environmental Pollution,* **150** (1), 107-124

Jones, A. & Hart, D.M., (1998) Comparison of laboratory toxicity tests for pesticides with field effects on earthworm populations: a review. *In* Sheppard, S.C., Brembridge,

J.D., Holmstrap, M. & Posthuma, L. *Advances in Earthworm Ecotoxicology*. Pensacola: Setac Press.
Jones, R., Parker, W., Khan, Z., Murthy, S. & Rupke, M., (2008). Characterization of sludges for predicting anaerobic digester performance. *Water Science and Technology,* **57** (5), 721-726
Kaltoft, P., (2001). Organic Farming in Late Modernity: At the Frontier of Modernity or Opposing Modernity? *Sociologia Ruralis,* **41** (1), 146-158
Kaparaju, P. & Rintala, J., (2011). Mitigation of greenhouse gas emissions by adopting anaerobic digestion technology on dairy, sow and pig farms in Finland. *Renewable Energy,* **36** (1), 31-41
Karakurt, I., Aydin, G. & Aydiner, K., (2012). Sources and mitigation of methane emissions by sectors: A critical review. *Renewable Energy,* **39** (1), 40-48
Kassam, A. & Brammer, H., (2013). Combining sustainable agricultural production with economic and environmental benefits. *Geographical Journal*, **179**, 11-18
Katovich, E.J. & Becker, R.L., (2005) *Weed Seed Survival in Anaerobic Digesters.* Minnesota.
Keats, D.M., (2000) *Interviewing: A Practical Guide for Students and Professionals*. University of New South Wales Press Ltd.
Kim, S. & Dale, B.E., (2005). Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. *Biomass and Bioenergy,* **29** (6), 426-439
Kimming, M., Sundberg, C., Nordberg, A., Baky, A., Bernesson, S., Noren, O. & Hansson, P.A., (2011). Life cycle assessment of energy self-sufficiency systems based on agricultural residues for organic arable farms. *Bioresource Technology,* **102** (2), 1425-1432
King, E.E., Smith, R.P., St-Pierre, B. & Wright, A.D.G., (2011). Differences in the Rumen Methanogen Populations of Lactating Jersey and Holstein Dairy Cows under the Same Diet Regimen. *Applied and Environmental Microbiology,* **77** (16), 5682-5687
Kirchmann, H. & Witter, E., (1992). Composition of fresh, aerobic and anaerobic farm animal dungs. *Bioresource Technology,* **40** (2), 137-142
Klavon, K.H., Lansing, S.A., Mulbry, W., Moss, A.R. & Felton, G., (2013). Economic analysis of small-scale agricultural digesters in the United States. *Biomass and Bioenergy,* **54** (0), 36-45
Krohn, S. & Damborg, S., (1999). On public attitudes towards wind power. *Renewable Energy,* **16** (1-4), 954-960
Lal, R., (2004). Carbon emission from farm operations. *Environment International,* **30** (7), 981-990
Lampkin, N., Measures, M. & Padel, S. eds. (2008) *2009 Organic Farm Management Handbook*, Ceredigion: Organic Research Group.
Landrum, M., Canas, J.E., Coimbatore, G., Cobb, G.P., Jackson, W.A., Zhang, B.H. & Anderson, T.A., (2006). Effects of perchlorate on earthworm (Eisenia fetida) survival and reproductive success. *Science of the Total Environment*, **363** (1-3), 237-244
Langdon, C.J., Piearce, T.G., Meharg, A.A. & Semple, K.T., (2003). Inherited resistance to arsenate toxicity in two populations of Lumbricus rubellus. *Environmental Toxicology and Chemistry,* **22** (10), 2344-2348

Lansing, S., Botero, R.B. & Martin, J.F., (2008). Waste treatment and biogas quality in small-scale agricultural digesters. *Bioresource Technology,* **99** (13), 5881-5890
Lantz, M., Svensson, M., Bjornsson, L. & Borjesson, P., (2007). The prospects for an expansion of biogas systems in Sweden - Incentives, barriers and potentials. *Energy Policy,* **35** (3), 1830-1843
Laossi, K.-R., Noguera, D.C., Decäens, T. & Barot, S., (2011). The effects of earthworms on the demography of annual plant assemblages in a long-term mesocosm experiment. *Pedobiologia*, **54** (2), 127-132
Larney, F.J. & Blackshaw, R.E., (2003). Weed seed viability in composted beef cattle feedlot manure. *Journal of Environmental Quality,* **32** (3), 1105-1113
Laverack, M.S., (1963) *The Physiology of Earthworms* London: Pergamon Press.
Lehtomaki, A., Huttunen, S. & Rintala, J.A., (2007). Laboratory investigations on co-digestion of energy crops and crop residues with cow manure for methane production: Effect of crop to manure ratio. *Resources Conservation and Recycling,* **51** (3), 591-609
Loake, C., (2001). Energy accounting and well-being — examining UK organic and conventional farming systems through a human energy perspective. *Agricultural Systems*, **70** (1), 275-294
Lobley, M. & Butler, A., (2010). The impact of CAP reform on farmers' plans for the future: Some evidence from South West England. *Food Policy,* **35** (4), 341-348
Lockie, S. & Halpin, D., (2005). The 'Conventionalisation' Thesis Reconsidered: Structural and Ideological Transformation of Australian Organic Agriculture. *Sociologia Ruralis,* **45** (4), 284-307
Loh, T.C., Lee, Y.C., Liang, J.B. & Tan, D., (2005). Vermicomposting of cattle and goat manures by Eisenia foetida and their growth and reproduction performance. *Bioresource Technology,* **96** (1), 111-114
Lowe, C.N. & Butt, K.R., (2005). Culture techniques for soil dwelling earthworms: A review. *Pedobiologia,* **49** (5), 401-413
Lukkari, T., Aatsinki, M., Vaisanen, A. & Haimi, J., (2005). Toxicity of copper and zinc assessed with three different earthworm tests. *Applied Soil Ecology,* **30** (2), 133-146
Lydeard, S., (1991). The Questionnaire as a Research Tool. *Family Practice,* **8** (1), 84-91
Lynne, G.D. & Rola, L.R., (1988). Improving attitude- behavior prediction models with economic variables- Farmer actions towards soil conservation. *Journal of Social Psychology,* **128** (1), 19-28
Ma, J., Scott, N.R., DeGloria, S.D. & Lembo, A.J., (2005). Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. *Biomass and Bioenergy,* **28** (6), 591-600
Mace, K., Morlon, P., Munier-Jolain, N. & Quere, L., (2007). Time scales as a factor in decision-making by French farmers on weed management in annual crops. *Agricultural Systems,* **93** (1-3), 115-142
Mader, P., FlieBbach, A., Dubois, D., Gunst, L., Fried, P. & Niggli, U., (2002). Soil Fertility and Biodiversity in Organic Farming. *Science*, **296** (5573), 1694-1697
Maranon, E., Salter, A.M., Castrillon, L., Heaven, S. & Fernandez-Nava, Y., (2011). Reducing the environmental impact of methane emissions from dairy farms by anaerobic digestion of cattle waste. *Waste Management,* **31** (8), 1745-1751

Masse, D.I., Masse, L., Hince, J.F. & Pomar, C., (2008). Psychrophilic anaerobic digestion biotechnology for swine mortality disposal. *Bioresource Technology,* **99** (15), 7307-7311
Masse, D.I., Talbot, G. & Gilbert, Y., (2011). On farm biogas production: A method to reduce GHG emissions and develop more sustainable livestock operations. *Animal Feed Science and Technology,* **166-67**, 436-445
Mataalvarez, J., Cecchi, F., Pavan, P. & Bassetti, A., (1993). Semidry Thermophilic Anaerobic-Digestion of Fresh and Pre-Composted Organic Fraction of Municipal Solid-Waste (Msw) - Digester Performance. *Water Science and Technology,* **27** (2), 87-96
Mathieu, J., Barot, S., Blouin, M., Caro, G., Decaëns, T., Dubs, F., Dupont, L., Jouquet, P. & Nai, P., (2010). Habitat quality, conspecific density, and habitat pre-use affect the dispersal behaviour of two earthworm species, Aporrectodea icterica and Dendrobaena veneta, in a mesocosm experiment. *Soil Biology and Biochemistry,* **42** (2), 203-209
McIntyre, G.I. & Hunter, J.H., (1975). Some effects of the nitrogen supply on growth and development of *Cirsium arvense*. *Canadian Journal of Botany-Revue Canadienne De Botanique,* **53** (24), 3012-3021
McNally, S., (2001). Farm diversification in England and Wales - what can we learn from the farm business survey? *Journal of Rural Studies,* **17** (2), 247-257
MEA, (2005) *Millenium Ecosystem Assessment.* London: Press, I., 2005017196.
Meynell, P.-J., (1982) *Methane: Planning a Digester,* 2nd ed. Dorchester: Prism Press.
Mitchell, A., (1997). Production of Eisenia fetida and vermicompost from feed-lot cattle manure. *Soil Biology & Biochemistry,* **29** (3-4), 763-766
Moeller, K. & Stinner, W., (2009). Effects of different manuring systems with and without biogas digestion on soil mineral nitrogen content and on gaseous nitrogen losses (ammonia, nitrous oxides). *European Journal of Agronomy,* **30** (1), 1-16
Moitzi, G., Amon, B., Amon, T., Kryvoruchko, V., Wagner-Alt, C., Hackl, E., Zechmeiser-Boltenstern, S. & Boxberger, J., (2007). Emissions of NH3, CH4 and N2O During storgae and after application of untreated and anaerobically digested slurry. *Bulletin USAMV-CN,* **63**, 368
Moller, K., (2009). Influence of different manuring systems with and without biogas digestion on soil organic matter and nitrogen inputs, flows and budgets in organic cropping systems. *Nutrient Cycling in Agroecosystems,* **84** (2), 179-202
Moorcroft, D., Whittingham, M.J., Bradbury, R.B. & Wilson, J.D., (2002). The selection of stubble fields by wintering granivorous birds reflects vegetation cover and food abundance. *Journal of Applied Ecology,* **39** (3), 535-547
Moreira, R., Sousa, J.P. & Canhoto, C., (2008). Biological testing of a digested sewage sludge and derived composts. *Bioresource Technology,* **99** (17), 8382-8389
Morrigan, T., (2010) *Peak Phosphorus- A potential Food Security Crisis.* Santa Barbara.
Muller, A., (2009). Sustainable agriculture and the production of biomass for energy use. *Climatic Change,* **94** (3-4), 319-331
Muller, C., (2007) *Anaerobic Digestion of Biodegradable Solid Waste in Low and Middle-Income Countries.*
Myers, A., (2006) *Organic Futures: The Case for Organic Farming* Devon: Green Books Ltd.

National Farmers Union. (2009). Anaerobic Digestion (Biogas)- an NFU Vision *NFU Briefing*.
Natural England, (2010) *Organic Entry Level Stewardship*.
NEA, U., (2011) *NEA- Technical report.* Cambridge: Group, U.N.E.W.C.M.
Neilson, R. & Boag, B., (2003). Feeding preferences of some earthworm species common to upland pastures in Scotland. *Pedobiologia*, **47** (1), 1-8
Neuhauser, E.F., Kaplan, D.L., Malecki, M.R. & Hartenstein, R., (1980). Materials supporting weight gain by the earthworm Eisenia foetida in waste conversion systems. *Agricultural Wastes*, **2** (1), 43-60
NNFCC, (2011) *The Official Information Portal on Anaerobic Digestion* [online]. http://www.biogas-info.co.uk/ [Accessed 2011].
Novak, S.M. & Fiorelli, J.L., (2010). Greenhouse gases and ammonia emissions from organic mixed crop-dairy systems: a critical review of mitigation options. *Agronomy for Sustainable Development*, **30** (2), 215-236
O'Leary, G.J. & Connor, D.J., (1998). A simulation study of wheat crop response to water supply, nitrogen nutrition, stubble retention, and tillage. *Australian Journal of Agricultural Research*, **49** (1), 11-19
OED, (2013) *Oxford English Dictionary*. Oxford University Press.
OF&G, (2006) OF&G Inspection and Certification Manual. *Land Management and Crop Production Standards.* Organic Farmers and Growers.
Oliver, D.M., Fish, R.D., Winter, M., Hodgson, C.J., Heathwaite, A.L. & Chadwick, D.R., (2012). Valuing local knowledge as a source of expert data: Farmer engagement and the design of decision support systems. *Environmental Modelling & Software*,
Oppenheim, A.N., (1992a) *Questionnaire Design and Attitude Measurement* London: Printers Publisher Ltd.
Oppenheim, A.N., (1992b) *Questionnaire Design, Interviewing and Attitude Measurement* London: Biddles Ltd.
Organic Farmers and Growers, (2006) OF&G inspection and Certification Control Manual. *Land Management and Crop Production Standards.*
Organic Food Federation, (2008) Production Standards. *Imported Fertiliser Material.* Nolfolk.
Ozores-Hampton, M., (1998). Compost as an alternative weed control method. *Hortscience*, **33** (6), 938-940
Ozores-Hampton, M., (Year) Organic Materials in Horticulture: An Industry Persepctive Sponsered by the Waste Utilization in Horticulture Working Group, Disney's Coronado Springs Resort, Lake Buena Vista: Horttechnology, 326-327.
Ozores-Hampton, M., Obreza, T.A., Stoffella, P.J. & Fitzpatrick, G., (2002). Immature compost suppresses weed growth under greenhouse conditions. *Compost Science & Utilization*, **10** (2), 105-113
Paavola, T. & Rintala, J., (2008). Effects of storage on characteristics and hygienic quality of digestates from four co-digestion concepts of manure and biowaste. *Bioresource Technology*, **99** (15), 7041-7050
Padel, S., (2001). Conversion to Organic Farming: A Typical Example of the Diffusion of an Innovation? *Sociologia Ruralis*, **41** (1), 40-61
Pain, B. & Jarvis, S., (1999) *Ammonia Emissions from Agriculture.* Aberystwyth.

Pattey, E., Trzcinski, M. & Desjardins, R., (2005). Quantifying the Reduction of Greenhouse Gas Emissions as a Resultof Composting Dairy and Beef Cattle Manure. *Nutrient Cycling in Agroecosystems,* **72** (2), 173-187

Pelosi, C., Bertrand, M., Capowiez, Y., Boizard, H. & Roger-Estrade, J., (2009). Earthworm collection from agricultural fields: Comparisons of selected expellants in presence/absence of hand-sorting. *European Journal of Soil Biology,* **45** (2), 176-183

Pfiffner, L. & Luka, H., (2007). Earthworm populations in two low-input cereal farming systems. *Applied Soil Ecology,* **37** (3), 184-191

Pimentel, D., (2003). Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts Are Negative. *Natural Resources Research,* **12** (2), 127-134

Pimentel, D., Berardi, G. & Fast, S., (1983). Energy Efficiency of Farming Systems - Organic and Conventional Agriculture. *Agriculture Ecosystems & Environment,* **9** (4), 359-372

POST, (2006) Carbon Footprint of Electricity Generation. *In* Technology, P.O.S.a. London: Parliamentary Copyright.

Power, A.G., (2010). Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **365** (1554), 2959-2971

Power, E.F., Kelly, D.L. & Stout, J.C., (2013). The impacts of traditional and novel herbicide application methods on target plants, non-target plants and production in intensive grasslands. *Weed Research,* **53** (2), 131-139

Quested, T. & Johnson, H., (2009) *Household Food and Drink Waste in the UK.* Banbury, 1-84405-430-6.

Radosevich, J. S. Holt & Ghersa, C., (1997) *Weed Ecology, Implications for Management,* 2nd ed. USA: John Wiley and Sons.

Rahmann, G., Oppermann, R., Paulsen, H.M. & Weissmann, F., (2009). Good, but not good enough? Research and development needs in Organic Farming. *Landbauforschung Volkenrode,* **59** (1), 29-40

Raven, R.P.J.M. & Gregersen, K.H., (2007). Biogas plants in Denmark: successes and setbacks. *Renewable & Sustainable Energy Reviews,* **11** (1), 116-132

REA, (2011) *Biofertiliser Certification Scheme*.

Rigby, D., Young, T. & Burton, M., (2001). The development of and prospects for organic farming in the UK. *Food Policy,* **26** (6), 599-613

Rodriguez, L.C. & O'Connell, D., (2011). Balance the blend of food and fuel. *Nature,* **476** (7360), 283-283

Rossi, J.-P., (2003a). Clusters in earthworm spatial distribution: The 7th international symposium on earthworm ecology · Cardiff · Wales · 2002. *Pedobiologia,* **47** (5-6), 490-496

Rossi, J., (2003b). Short-range structures in earthworm spatial distribution. *Pedobiologia,* **47**, 582-587

Rossi, J.P. & Lavelle, P., (1998). Earthworm aggregation in the savannas of Lamto (Cote d'Ivoire). *Applied Soil Ecology,* **7** (2), 195-199

Rossi, J.P., Lavelle, P. & Albrecht, A., (1997). Relationships between spatial pattern of the endogeic earthworm Polypheretima elongata and soil heterogeneity. *Soil Biology & Biochemistry,* **29** (3-4), 485-488

Rygg, B.J., (2012). Wind power-An assault on local landscapes or an opportunity for modernization? *Energy Policy,* **48**, 167-175

Salter, A., (2011) *On-farm energy and emissions calculator* [online]. University of Southampton. Available from: http://www.anaerobic-digestion.soton.ac.uk/ [Accessed 2011].

Salter, A. & Banks, C.J., (2009). Establishing an energy balance for crop-based digestion. *Water Science and Technology,* **59** (6), 1053-1060

Sandars, D.L., Audsley, E., Canete, C., Cumby, T.R., Scotford, I.M. & Williams, A.G., (2003). Environmental benefits of livestock manure management practices and technology by life cycle assessment. *Biosystems Engineering,* **84** (3), 267-281

Santos, M.J.G., Ferreira, M.F.L., Cachada, A., Duarte, A.C. & Sousa, J.P., (2012). Pesticide application to agricultural fields: effects on the reproduction and avoidance behaviour of Folsomia candida and Eisenia andrei. *Ecotoxicology,* **21** (8), 2113-2122

Saxe, J.K., Impellitteri, C.A., Peijnenburg, W.J.G.M. & Allen, H.E., (2001). Novel model describing trace metal concentrations in the earthworm, Eisenia andrei. *Environmental Science & Technology,* **35** (22), 4522-4529

Schaefer, M., (2004). Assessing 2,4,6-trinitrotoluene (TNT)-contaminated soil using three different earthworm test methods. *Ecotoxicology and Environmental Safety,* **57** (1), 74-80

Schittenhelm, S., (2008). Chemical composition and methane yield of maize hybrids with contrasting maturity. *European Journal of Agronomy,* **29** (2-3), 72-79

Schlamadinger, B., Robertson, K. & Woess-Gallasch, S., (2006) *Task 38: Greenhouse Gas Balances of Biomass and Bioenergy Systems.* Stockholm, Sweden, ExCo58.

Schoon, B. & Te Grotenhuis, R., (2000). Values of farmers, sustainability and agricultural policy. *Journal of Agricultural & Environmental Ethics,* **12** (1), 17-27

Schulman, M.D. & Armstrong, P.S., (1989). The Farm Crisis- An Analysis of Social Psychological Distress among North-Carolina Farm Operators. *American Journal of Community Psychology,* **17** (4), 423-441

Seadi, T.A. & Lukehurst, C., (2012) *Quality management of digestate from biogas plants used as fertiliser*.

Seufert, V., Ramankutty, N. & Foley, J.A., (2012). Comparing the yields of organic and conventional agriculture. *Nature,* **485** (7397), 229-U113

Sheehan, C., Kirwan, L., Connolly, J. & Bolger, T., (2007). The effects of earthworm functional group diversity on earthworm community structure. *Pedobiologia,* **50** (6), 479-487

Sheppard, S.C., Evenden, W.G. & Anderson, A.J., (1992). Multiple Assays of Uranium Toxicity in Soil. *Environmental Toxicology and Water Quality,* **7** (3), 275-294

Sims, R.W. & Gerard, B.M., (1985) *Earthworms: Keys and Notes for the Identification and Study of the Species* London: Brill Archive.

SKM Enviros, (2011) *Analysis of characteristics and growth assumptions regarding AD biogas combustion for heat, electricity and transport and biomethane production and injection to the Grid.* Manchester, 09/06/2010.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes & Sirotenko, O., (2007) Agriculture. *In* Rypdal, K. &

Githendu, M.w. *Climate Change 2007: Working Group III: Mitigation of Climate Change* Cambridge: Cambridge University Press.
Social Research Assocaition, (2003) *Ethical Guidelines* [online]. www.the-sra.org.uk [Accessed 2011]
Society., T.R., (2009) *Reaping the benefits.* London.
Soil Association, (2008) *Anaerobic Digestion.* Bristol.
Soil Association, (2009a) Soil Association Organic Standards for Producers. *Manure, Compost and Plant Wastes.* 87-96.
Soil Association, (2009b) Soil Association Organic Standards for Producers. *Manure, Compost and Plant Wastes.* 87-96.
Sommer, S.G. & Hutchings, N., (1995). Techniques and strategies for the reduction of ammonia emission from agriculture. *Water, Air, & Soil Pollution,* **85** (1), 237-248
Sommer, S.G. & Olesen, J.E., (2000). Modelling ammonia volatilization from animal slurry applied with trail hoses to cereals. *Atmospheric Environment*, **34** (15), 2361-2372
Spurgeon, D.J., Svendsen, C., Kille, P., Morgan, A.J. & Weeks, J.M., (2004). Responses of earthworms (Lumbricus rubellus) to copper and cadmium as determined by measurement of juvenile traits in a specifically designed test system. *Ecotoxicology and Environmental Safety,* **57** (1), 54-64
Spurgeon, D.J. & Weeks, J.M., (1998) Evaluation of Factors influencing results from laboratory toxicity tests with earthworms. *In* Sheppard, S., Bembridge, J. & Holmstrup, M. *Advances in Earthworm Ecotoxicology.* Pensacola, FL.: SETAC Press,.
Stephenson, A.L., Dennis, J.S. & Scott, S.A., (2008). Improving the sustainability of the production of biodiesel from oilseed rape in the UK. *Process Safety and Environmental Protection,* **86** (6), 427-440
Stephenson, A.L., Dupree, P., Scott, S.A. & Dennis, J.S., (2010). The environmental and economic sustainability of potential bioethanol from willow in the UK. *Bioresource Technology,* **101** (24), 9612-9623
Stephenson, G.L., Kaushik, A., Kaushik, N.K., Solomon, K.R., Steele, T. & Scroggins, R.P., (1998) Use of an avoidance-response test to assess the toxicity of contaminated soils to earthworms. *In* Sheppard, S., Bembridge, J., Holmstrup, M. & Posthuma, L. *advances in Earthworm Ecotoxicology.* Pensacola: Setac Press.
Sutherland, L.A., (2010). Environmental grants and regulations in strategic farm business decision-making: A case study of attitudinal behaviour in Scotland. *Land Use Policy,* **27** (2), 415-423
Svendsen, C. & Weeks, J.M., (1997a). Relevance and Applicability of a Simple Earthworm Biomarker of Copper Exposure. II. Validation and Applicability under Field Conditions in a Mesocosm Experiment withLumbricus rubellus. *Ecotoxicology and Environmental Safety,* **36** (1), 80-88
Svendsen, C. & Weeks, J.M., (1997b). A Simple Low-Cost Field Mesocosm for Ecotoxicological Studies on Earthworms. *Comparative Biochemistry and Physiology Part C: Pharmacology, Toxicology and Endocrinology,* **117** (1), 31-40
Svensson, K. & Pell, M., (2001). Soil microbial tests for discriminating between different cropping systems and fertiliser regimes. *Biology and Fertility of Soils,* **33** (2), 91-99

Swindal, M.G., Gillespie, G.W. & Welsh, R.J., (2010). Community digester operations and dairy farmer perspectives. *Agriculture and Human Values,* **27** (4), 461-474

Syers, J. & Springett, J., (1984). Earthworms and soil fertility. *Plant and Soil,* **76** (1), 93-104

Symons, G.E. & Buswell, A.M., (1933). The Methane Fermentation of Carbohydrates. *Journal of American Chemical Society,* **55**, 2028-2036

Tafdrup, S., (1995). Viable energy production and waste recycling from anaerobic digestion of manure and other biomass materials. *Biomass and Bioenergy,* **9** (1-5), 303-314

TEEB, (2013) *The Economics of Ecosystems and Biodiversity* [online]. http://www.teebweb.org/ [Accessed 2013].

The Carbon Trust, (2012) *Carbon Footprinting- The Next Step to Reducing your Emissions.* London.

Thomsen, I.K., Laegdsmand, M. & Olesen, J.E., (2010). Crop growth and nitrogen turnover under increased temperatures and low autumn and winter light intensity. *Agriculture Ecosystems & Environment,* **139** (1-2), 187-194

Tranter, R.B., Swinbank, A., Jones, P.J., Banks, C.J. & Salter, A.M., (2011). Assessing the potential for the uptake of on-farm anaerobic digestion for energy production in England. *Energy Policy,* **39** (5), 2424-2430

Truss, L., (2003) *Eats, Shoots and Leaves* London: Profile Books.

Tuomisto, H.L., Hodge, I.D., Riordan, P. & Macdonald, D.W., (2012). Does organic farming reduce environmental impacts? - A meta-analysis of European research. *Journal of Environmental Management,* **112**, 309-320

United Nations, (1998) *Kyoto Protocol to the United Nations Framework Convention on Climate Change* [online]. http://unfccc.int/resource/docs/convkp/kpeng.pdf [Accessed 2011].

United Nations, (2008) *End Poverty 2015, Millenium development goals* [online]. http://www.un.org/millenniumgoals/ [Accessed 2009].

van Dam, J., Junginger, M. & Faaij, A.P.C., (2010). From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. *Renewable & Sustainable Energy Reviews,* **14** (9), 2445-2472

Van Gestel, C.A.M., (1992). Validation of earthworm toxicity tests by comparison with field studies: A review of benomyl, carbendazim, carbofuran, and carbaryl. *Ecotoxicology and Environmental Safety,* **23** (2), 221-236

Van Gestel, C.A.M. & Weeks, J.M., (2004). Recommendations of the 3rd International Workshop on Earthworm Ecotoxicology, Aarhus, Denmark, August 2001. *Ecotoxicology and Environmental Safety,* **57** (1), 100-105

Vanpraagh, A.D., Gavaghan, P.D. & Sykora, J.L., (1993). Giardia-Muris Cyst Inactivation in Anaerobic Digester Sludge. *Water Science and Technology,* **27** (3-4), 105-109

Walker, M., Banks, C.J. & Heaven, S., (2009). Development of a coarse membrane bioreactor for two-stage anaerobic digestion of biodegradable municipal solid waste. *Water Science and Technology,* **59** (4), 729-735

Walla, C. & Scheneeberger, W., (2003) Survey of Farm Biogas Plants with Combined Heat and Power Production in Austria. *International Nordic Bioenergy 2003 Conference.* Finland.

Ward, A.J., Hobbs, P.J., Holliman, P.J. & Jones, D.L., (2008). Optimisation of the anaerobic digestion of agricultural resources. *Bioresource Technology*, **99** (17), 7928-7940

Wathes, C.M., Holden, M.R., Sneath, R.W., White, R.P. & Phillips, V.R., (1997). Concentrations and emission rates of aerial ammonia, nitrous oxide, methane, carbon dioxide, dust and endotoxin in UK broiler and layer houses. *British Poultry Science*, **38** (1), 14-28

Webb, J., Chadwick, D. & Ellis, S., (2004). Emissions of ammonia and nitrous oxide following incorporation into the soil of farmyard manures stored at different densities. *Nutrient Cycling in Agroecosystems*, **70** (1), 67-76

Weidman, T. & Minx, J., (2008) A definition of "Carbon Footprint". *In* Pertsova, P.P. *Ecological Economics Research Trends.* Hauppauge NY: Nova Science Publishers, 1-11.

Weiland, P., (2000). Anaerobic waste digestion in Germany-status and recent developments. *Biodegradation*, **11** (6), 415-21

Weiland, P., (2010). Biogas production: current state and perspectives. *Applied Microbiology and Biotechnology*, **85** (4), 849-860

Weiske, A., Vabitsch, A., Olesen, J.E., Schelde, K., Michel, J., Friedrich, R. & Kaltschmitt, M., (2006). Mitigation of greenhouse gas emissions in European conventional and organic dairy farming. *Agriculture Ecosystems & Environment*, **112** (2-3), 221-232

Wengraf, T., (2001) *Qualitative research interviewing* London: SAGE Publications Ltd.

Westerman, P.R., Heiermann, M., Pottberg, U., Rodemann, B. & Gerowitt, B., (2012). Weed seed survival during mesophilic anaerobic digestion in biogas plants. *Weed Research*, **52** (4), 307-316

Whalen, J.K., Parmelee, R.W. & Edwards, C.A., (1998). Population dynamics of earthworm communities in corn agroecosystems receiving organic or inorganic fertilizer amendments. *Biology and Fertility of Soils*, **27** (4), 400-407

WHO, (2013) *Food Security* [online]. http://www.who.int/trade/glossary/story028/en/ [Accessed 2013].

Wiese, A.F., Sweeten, J.M., Bean, B.W., Salisbury, C.D. & Chenault, E.W., (1998). High temperature composting of cattle feedlot manure kills weed seed. *Applied Engineering in Agriculture*, **14**, 377-380

Willock, J., Deary, I.J., McGregor, M.M., Sutherland, A., Edwards-Jones, G., Morgan, O., Dent, B., Grieve, R., Gibson, G. & Austin, E., (1999). Farmers' attitudes, objectives, behaviors, and personality traits: The Edinburgh Study of Decision Making on Farms. *Journal of Vocational Behavior*, **54** (1), 5-36

Wolsink, M., (2000). Wind power and the NIMBY-myth: institutional capacity and the limited significance of public support. *Renewable Energy*, **21** (1), 49-64

Wolsink, M., (2007). Wind power implementation: The nature of public attitudes: Equity and fairness instead of 'backyard motives'. *Renewable & Sustainable Energy Reviews*, **11** (6), 1188-1207

World Bank, (2011) *GEM Commodities* [online]. http://data.worldbank.org/data-catalog/commodity-price-data [Accessed 2012].

WRAP, (2008) *Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials.* Wellingborough.

Wulf, S., Maeting, M. & Clemens, J., (2002a). Application Technique and Slurry Co-Fermentation Effects on Ammonia, Nitrous Oxide , and Methane emissions after Spreading: I. Ammonai Volatization. *Journal of Environmental Quality,* **31**, 1789-1794

Wulf, S., Vandre, R. & Clemens, J., (2002b). Mitigation options for CH4, N2O and NH3 emissions from slurry management. *Non-C02 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects,* 487-492

Xiao, H., Zhou, Q.X. & Liang, J.D., (2004). Single and joint effects of acetochlor and urea on earthworm Esisenia foelide populations in phaiozem. *Environmental Geochemistry and Health,* **26** (2-3), 277-283

Yiridoe, E.K., Gordon, R. & Brown, B.B., (2009). Nonmarket cobenefits and economic feasibility of on-farm biogas energy production. *Energy Policy,* **37** (3), 1170-1179

Zhou, Q. & Liang, J., (2003). Single and binary-combined toxicity of methamidophos, acetochlor and copper acting on earthworms Esisenia foelide. *Bulletin of Environmental Contamination and Toxicology,* **71** (6), 1158-1166

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December 2008

Dear Sir / Madam

UNIVERSITY OF READING SURVEY ON PRODUCING BIOGAS ON FARMS FOR FUEL

Over recent months there has been much discussion about farmers being involved in the production of bio-fuels to both raise incomes and substitute for oil. At present, we are engaged in an enquiry into the opportunities for producing biogas for fuel on farms on behalf of the Rural Economy and Land Use Programme of the Research Councils and Defra (www.relu.ac.uk). The relevant rural and agricultural organisations and agencies are aware of the project.

We are writing to invite you to take part in this important project. It is being carried out by the School of Agriculture, Policy and Development at the University of Reading, the largest such institution in the UK and one which has contributed much to British agriculture over 110 years. Whilst we are making much use of past studies, and carrying out our own desk-based calculations, we need information from a national spread of farm businesses. Thus, we are seeking the help of some 2000 farmers and landowners <u>in total confidence</u>.

The questionnaire which we would like you to fill in has been designed to take as little time as possible. However, we realise it may be a nuisance and apologise for this now. Nevertheless, the search for alternative enterprises and cheaper fuel is crucially important and it is our belief that, by filling in the questionnaire, you will be making a direct contribution to the framing of effective policies and the provision of sound advice and information.

The enclosed questionnaire is in three parts:
A. Questions about you and the farm business you run;
B. Questions about your experiences with diversification and alternative enterprises; and
C. Questions to determine whether biogas production would fit in on your farm and whether you would consider investing in the necessary plant.

We do hope you will be able to find time to answer our questions and <u>to return the completed form in the reply-paid envelope provided</u>. As already stated, your answers will, of course, be treated in the strictest confidence. Please do not hesitate to contact me if you wish.

Yours faithfully

R.B. Tranter.

Richard Tranter
Director

Part A

If possible, we would like the main decision-maker to answer this. So that we can get some idea of what sort of farm business you run, would you please tell us about your current situation (i.e. 2008 harvest year):

1. Total area farmed: [ ] ha
   of which: and under what arrangements:

Cereals	ha
Other arable crops	ha
Leys	ha
Permanent pasture	ha
Rough grazing	ha
Other(specify)	ha

Owner-occupied	ha
Share-farmed	ha
Land let out by you	ha
Rented on full agricultural tenancy	ha
Rented on farm business tenancy	ha
Rented on other arrangements	ha

2. Current livestock numbers:

Dairy cattle	
Beef cattle	
Sheep	
Breeding sows	

Finishing pigs	
Laying hens	
Other poultry(please specify)	
Other livestock(please specify)	

3. Which description best fits your type of farming? (please tick all that apply)

Dairying	
LFA sheep/cattle	
Lowland sheep/cattle	
General cropping	
Specialist cereals	

Mixed livestock and arable	
Pigs/poultry	
Horticulture	
Other (please specify)	

4. Are you a full-time or part-time farmer: Full-time [ ] Part-time [ ]

   Total number of regular workers including you and your family : Full-time [ ] Part-time [ ]

5. What is your typical annual spend on contractors? £

6. What is your role on the farm? Farmer [ ] Partner [ ] Manager [ ] Other [ ]

   When did you start in this position? [ ]

7. What is the legal status of your farm business?

   Sole proprietorship [ ] Company [ ] Other [ ]

   Family partnership [ ] Other partnership [ ]

8. Your age: [ ] Your gender: male [ ] female [ ]

9. Have you identified a successor?
   Definitely [ ] Very likely [ ] Possibly [ ] Unlikely [ ] [ ]
   Definitely not

10. The age you left full-time education: [ ]

    Have you had any formal agricultural education? Yes [ ] No [ ]

11. What proportion of the income of **your household in a typical year** comes from sources other than the farm business? %

    If **any other source**, what is the nature of it? [ ]

12. Please indicate how well your business is doing by ticking one of the following statements:

At the moment my business is not profitable and may not survive ☐
At the moment my business is not profitable but can survive for a while ☐
Profits are down, but my business should be able to weather this crisis ☐
I am managing to maintain my profit level ☐
I have managed to increase profits ☐

13. Do you think you will still be farming in **ten** years time? Yes ☐ No ☐

If **No,** which of these statements best describes your likely situation in ten years time?

You will have retired at the normal age	☐	**having:**	sold your farm	☐
You will have taken early retirement	☐		given up your tenancy	☐
You will have taken up other employment	☐		passed your farm to a successor	☐
			rented out your farm	☐
			abandoned the land	☐

Part B

So that we can get some idea about your experience and interest in diversification activities and agri-environment schemes, would you please tell us:

14. Have you applied, or are you planning to apply, to the Entry Level and/or Higher Level Environmental Stewardship Scheme? (please tick one)

No	☐	Planning to apply to Entry Level	☐
Applied to Entry Level	☐	Planning to apply to both Entry and Higher Level	☐
Applied to both Entry and Higher Level	☐		

15. Do you still have a live CSS agreement? Yes ☐ No ☐

16. Do you still have a live ESA agreement? Yes ☐ No ☐

17. Are you in a Nitrate Vulnerable Zone (NVZ)? Yes ☐ No ☐

If **Yes,** what proportion of your land is in a NVZ? ____ %

18. What proportion, if any, of your land is organic? ____ %

19. Have you diversified into any non-traditional farming enterprises that use farm land, labour or capital? (please tick all that apply)

Growing energy crops (miscanthus or coppice)		On farm food processing/grading/packaging	
Industrial OSR on set-aside land		Direct sales (including farm shop)	
B&B accommodation		Contracting or haulage	
Caravans		Equine	
Holiday cottages		Other (please specify):	
Residential or commercial property lets			

20. Have you previously investigated the potential of producing biogas for fuel on your farm? Yes ☐ No ☐

21. Do you currently have a slurry management problem? Yes ☐ No ☐

Part C
Please carefully read the following explanation of what on-farm anaerobic digestion (AD) is. Then answer the questions below:

AD is a proven technology that uses natural bacteria to ferment organic material, in a closed vessel, to produce biogas and bio-fertiliser. The biogas (largely methane) can be used directly to provide heat, electricity via a combined heat and power unit, or can be cleaned for use as vehicle fuel or injection into the national gas grid. Benefits of AD include the capture of methane that would otherwise be emitted from materials as they decompose and that AD leads to a reduction in the odour of raw slurry whilst reducing the number of pathogens and viable weed seeds. Because AD does not reduce the nutrient content of material put through it, any residues can be used as bio-fertiliser with improved nutrient availability as compared with raw slurry.

AD can be deployed at scales from a few tens of kWs to several MWs depending on the availability of biomass material as feedstock. Farm derived feedstocks include animal slurries and any crops currently grown for silage including wheat, maize, and grasses. Where available, imported feedstocks, including food wastes, can be used and may provide a gate fee income. Little financial data for the UK is yet available. However, a medium-sized operation using feedstock equivalent to the slurry from 200 cows and maize silage from some 350 ha might require an investment of £400,000 which, allowing for the cost of finance, would produce a net return of £300 per ha per year from selling electricity.

22. Would you consider investing in a biogas digester in the next 5 years? Yes ☐ No ☐ Maybe ☐

23. Please indicate by a tick against this list of possible benefits of adopting AD how important they seem to you:

	Very important	Important	Not very important	Of no importance
Improve farm profit				
Reduce pollution / contamination risk				
Reduce farm's carbon footprint				
Other reason (please state):				

24. Please indicate by a tick against this list of possible obstacles to AD how important they seem to you:

	Very important	Important	Not very important	Of no importance
The returns seem too low				
Establishment costs seem too high				
I don't think I could learn how to run it				
I don't have enough spare labour to operate it				
The residues would not be worthwhile as a fertiliser				
My tenancy agreement would not permit it				
Difficulty obtaining planning permission				
Growing feedstock would disrupt my rotation				
Little information available				
Other reason (please state):				

25. If you were to install a digester, do you think you could do much of the building work yourself to reduce costs? Yes ☐ No ☐

26. If you were to install a digester for biogas production, please insert below the area you might plant for feedstock on the different sorts of land on your farm:

	Area (ha)
Cereal land	
Land growing other arable crops	
Land growing leys	
Land under permanent pasture	
Rough grazing land	
Other (specify)	

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October 2009

Dear Sir / Madam

UNIVERSITY OF SOUTHAMPTON SURVEY INTO ON-FARM ANAEROBIC DIGESTERS IN ORGANIC FARMING SYSTEMS

Over recent months there has been much discussion about farmer's involvement in the production of bio-fuels both in relation to raising incomes and supporting renewable energy production. As part of my PhD research, I am particularly interested in the implications of incorporating anaerobic digestion, and the production of biogas, into organic farming systems. My research is being sponsored and supported by the Rural Economy and Land Use Programme (www.relu.ac.uk), and the Universities of Southampton, Reading and Exeter, and is under the supervision of Professor Banks, Professor Poppy and Professor Winter.

I appreciate the importance of farmer's opinions on this matter, and so invite you to take part in the survey enclosed. It has been designed to take as little time as possible and I thank you in advance for your help. Please return the completed form in the reply-paid envelope provided. Your answers will, of course, be treated in the strictest confidence. Please do not hesitate to contact me for any further information or with questions you may have.

Yours faithfully

Laura Clements
PhD student

So that I can get some idea of what sort of farm business you run, please tell me about your current situation (i.e. harvest year 2008 or 2009 if available):

1. Total area farmed: ______ ha
2. Of which:

Cereals	ha
Other arable crops	ha
Leys	ha
Permanent pasture	ha
Rough grazing	ha
Other (specify)	ha

3. Current livestock number:

Dairy cattle		Finishing pigs	
Beef cattle		Laying hens	
Sheep		Other poultry	
Breeding sows		Other livestock	

4. Which description best fits your type of farming? (Please tick all that apply)

Dairying		Mixed livestock and arable	
LFA sheep/cattle		Pigs/poultry	
Lowland sheep/cattle		Horticulture	
General cropping		Other (please specify)	
Specialist cereals			

5. You Age: ____________

6. Have you had any formal agricultural education? Yes ☐ No ☐

7. What proportion, if any, of your land is organic? ____________%

8. What proportion, if any, of your land is classified as a NVZ? ____________%

9. Do you currently have a slurry management problem? Yes ☐ No ☐

10. Have you previously investigated the potential of producing biogas on your farm?

Yes ☐ No ☐

11. Please state any previous sources of knowledge you have of anaerobic digestion and the production of biogas:

____

____

____

Please carefully read the following explanation of what on-farm anaerobic digestion (AD) is. Then answer the questions below:

AD is a proven technology that uses natural bacteria to ferment organic material, in a closed vessel, to produce biogas and bio-fertiliser. The biogas (largely methane) can be used directly to provide heat, electricity via a combined heat and power unit, or can be cleaned for use as vehicle fuel or injection into the national gas grid. Benefits of AD include the capture of methane that would otherwise be emitted from materials as they decompose and that AD leads to a reduction in the odour of raw slurry whilst reducing the number of pathogens and viable weed seeds. Because AD does not reduce the nutrient content of material put through it, any residues can be used as bio-fertiliser with improved nutrient availability as compared with raw slurry.

AD can be deployed at scales from a few tens of kWs to several MWs depending on the availability of biomass material as feedstock. Farm derived feedstocks include animal slurries and any crops currently grown for silage including wheat, maize, and grasses. Where available, imported feedstocks, including food wastes, can be used and may provide a gate fee income. Little financial data for the UK is yet available. However, a medium-sized operation using feedstock equivalent to the slurry from 200 cows and maize silage from some 350 ha might require an investment of £400,000 which, allowing for the cost of finance, would produce a net return of £300 per ha per year from selling electricity.

12. Would you consider investing in a biogas digester in the next 5 years?

Yes ☐ No ☐ Maybe ☐

13. Please indicate by a tick against this list of possible benefits of adopting AD how important they seem to you:

	Very important	Important	Not very important	Of no importance
Improve farm profit				
Reduce pollution / contamination risk				
Reduce farm's carbon footprint				
Other reason (please state):				

14. Please indicate by a tick against this list of possible obstacles to AD how important they seem to you:

	Very important	Important	Not very important	Of no importance
The returns seem too low				
Establishment costs seem too high				
Don't think I could learn how to run it				
Don't have enough spare labour to operate it				
The residues would not be worthwhile as a fertiliser				
My tenancy agreement would not permit it				
Difficulty obtaining planning permission				
Growing feedstock would disrupt my rotation				
Little information available				
Other reason (please state):				

Focus group/ interview opportunity.

Farmer involvement enables us to better understand the barriers and issues surrounding AD implication. I am intending to carry out a focus group study and/ or interviews with organic farmers in the near future. **If you are interested in taking part, or would like further information**, please tick the box and provide your contact details below: ☐

Name:____

Email:____

Tel:____

Address:____

____

______________________________Post code:__________

Preferable date availability (please tick all applicable) :

April ☐ May ☐ June ☐ July ☐ August ☐

Thank you for your help. Please return the questionnaire in the reply-paid envelope.

Interview Questions:

<u>1. Please tell me your name and a bit about your farm. (3mins) (personal)</u>

- Fill any gaps from the original questionnaire
- Description of farm (size, stock, crop, tenant, owned etc)
- How long have then been farming/ organic
- Any non-agricultural enterprises on the farm
- Identify if land owner or farm manager

<u>2. Please tell me what farming organically means to you. (5mins) (personal)</u>

- What type of organic farmer are they
- What motivates them to farm organically
- What issues have most emphasis as being organic
- What are the main differences between farming organically V's conventionally (management and outlook differences)

<u>3. What role does farming organically play in reducing pollution? (5mins) (general)</u>

- Whether this is a role for organic farming- are they doing enough or should they continue to strive to improve
- What sources of pollution do they have/ are they aware of on their farms
- How they do it on their farm (ask or examples)
- Should it be the role as an organic farmer to strive to do more?
- Do they have any examples on their farm?

Comment
May be brought up in previous question- try and extend to include points above.

<u>4. What influences and encouragement do you have to reduce pollution and where are these sources of encouragement from. (5mins) (general)</u>

- See if they talk about own self motivation/ personal views to reduce
- What impact does government policy have (is there a current drive?)
- Whether certifying bodies have an impact on their behaviours
- Are they offered any opportunities that they are aware of?
- Do they talk about any problems with the encouragement?

<u>5. LIVESTOCK FARMS ONLY! How do you find manure management differs to that of conventional farming? Are you aware of, or do you expect there to be any major changes in management in the near future? (5mins) (general)</u>

- Describe the major differences.
- What management do they currently do?
- Are they aware of changes they will be expected to make- how will they go about it?

<u>6. How much do you know about the production of biogas through anaerobic digestion? From now on, I shall refer to anaerobic digestion as AD. How suitable would it fit within the values and the practicality of organic farms? (10mins) (both)</u>

- Find out whether their comments are generally positive of negative
- See how much they know
- See where they have got their information from
- Do they consider them as a means of biogas production or reduce pollution or a source of manageable fertiliser or all?
- What are their experiences of AD
- Is there any conflict between the farmer's opinions and any organisations?

7. Have you considered AD for your farm? (personal)

- No- go to a)
- Yes- go to b)

a) No: If not-why not? Have you considered any technology or energy generation on your farm? (2-5mins) (personal)

- Talk about other technologies, what attracted them
- Do you suspect it will be a future issue?

b) If yes, what was your main reason for this? What has been you experience of this process? (5-10mins) (personal)

- Whether it is a realistic technology for organics
- What first attracted them to AD- esp. over alternatives?
- What was their process and how easy the process was
- At what stage they are at and the difficulties they have so far encountered
- What level these difficulties are (governmental to farmer individual level)
- Why they would not consider AD (where these barriers lie)
- How aware are they of government/ local help
- Why they decided to invest time/ money in this form and not others?
- Have they encountered any problems

8. What are the barriers and benefits of AD for organic farmers? Are these different from those of conventional farms? (5mins) (general)

- To produce a list of barriers and benefits
- Lack of research? Evidence? Investment opportunities?
- To identify what barriers existed (local, physical, govn., financial, public etc)
- Outline their fears in investing in a new technology
- Maybe extend into pro's of AD if interview is lacking barriers.
- Is there a way that these barriers can be overcome?
- Where can more help be given?

9. What other technologies are you aware of for small scale on-farm generation of energy? How suitable are these for organic farms? Would you consider any for your farm? (5-10mins) (both)

- Find out if they know of any examples- which are most frequently mentioned?
- See what they know about the topic- is it suited to organics?
- Find out past experiences
- Is there a current drive for renewable energies being felt
- See how much they have thought about renewable energy on their farms.

10. Where do you get or where would you go for information regarding renewable energy technology. Which sources do you trust and which are more useful? (5mins) (personal)

- Identify which they have accessed, or have been available/ aware of
- Which are the best ways to communicate with farmers
- What type of information are they looking for (what stage in the process?)
- Both personal sought and all farmers
- Any of these in particular for AD?
- Quality of current information.
- Is enough provided or are there gaps? Where?

<u>11. The audience for this report may include those in power to make changes. Is there anything you wish to add that would help support organic farms with helping to achieve key governmental issues and targets of environmental sustainability such as renewable energies and reductions in pollution, and anything in particular in relation with AD. (2-5mins) (general)</u>

- See if there are any key features they feel have been missed
- Give them the opportunity to have an opinion of comment passed up to influencing bodies.

<u>12. I believe we have covered everything I wanted to, so would like to take this opportunity to thank you very much for your time and input. Finally, are there any closing comments you wish to make, or issues you feel have not been discussed? (2mins) (general)</u>

- Draw together findings/ opinions
- Ensure general conclusion is acceptable / views have been understood
- Offer final opportunity to make further comments on the topic and interview process

Anaerobic digestion in an organic farming environment

Agricultural production area:

Does the farmer have a map of fields? (with scale if possible?)

Total FARMED area (excluding woodland)___________ha

Details of livestock ____

____

____

Total number of fields ______________________________

How long do cows spend on field:__________________months

What bedding is used in barn: __________________________________

How much bedding (total/yr if possible):_________________________

General livestock diet (%grass, silage, fodder, concentrates other. Is this imported or self supplied (% of total crops)

____

____

____

Current waste storage facilities:

Current volume manure available ________________________

What volume is returned to field _________________________________

Estimate tonnage of crops left on fields as cover crops ____________

Current methods of spreading ____________________________
Volume spreader can hold ____________________m_3

Any additional nutrients added

____

Any details of N, P, K, % DW or VS of manure?

____

What and how much waste crop material do you have?
____

____

Farmed fields

What is your typical farm rotation?____

____

Crop production

Use of machinery for the production of each crop type- Completed for one complete year od rotation (doesn't matter which as long as they are all from the same rotational year). Please write crop type in top row and provide in as much details machinery operation use as possible. Please complete **g/a**= gallons of fuel per year used for that machine for the production of that crop (estimates are ok- if gallons are unknown, please provide mileage if known). Also please include **p/a**= number of times the machine is used in the production of that crop for one year.

Crop type:					
Machinery	Load (ton) if relevant	p/a	g/a	p/a	g/a
Subsoiler					
Plough					
Harrow					
Disc					
Drill					
Precision drill					
Roll					
Spray					
Mechanical hoe					
Maize hoe					

Comb harrow						
Combine						
Forage harvester						
Ensile						
Mow						
Load forage						
Bale						
Beet harvester						

Other notes or as much detail on machinery use as possible:____

____

____

____

What cover crop/ green fertilisers do you use?

____

Considering AD options:

Available surface area for building AD plant _________________________ m^2

Distance between waste stores and potential AD plant __________________m

Distance between barns (manure collection points) and AD plant ____________m

UNIVERSITY OF Southampton
School of Biological Sciences

Initial Evaluation of RELU Organic AD Model data for xxxxxx xxxxxx Farm, Wiltshire.

4th May 2011

Laura Clements

School of Biological Sciences
Life Sciences Building
University of Southampton
Highfield
Southampton
SO17 1BJ

Please note; the information contained within this report are best case estimates generated from our independently developed AD tool. They should not be used alone to make decisions on AD requirements for your farming system. Always consult a specialist regarding actual suitable dimensions and potential gas production.

Current practice

Summary
Mixed organic farm
Total 604 ha of land
Average journey to field (2 km =1.75 miles)

Crop include
- Wheat grain- 109 ha (grain tFM 5.2 ha^{-1}) (straw 2.3 t ha^{-1})
- Triticale (and rye) - 27ha (7 ha) total 34ha (grain tFM 4.7 ha^{-1})
- Spring barley- 53 ha (grain tFM 7 ha^{-1})
- Beans- 83 ha (grain tFM 3 ha^{-1})
- Green manure (vetch and mustard)- 84 ha
- Clover pasture- 122 ha (yr 1 hay& graze 50 ha, yr 2 graze 20-22 ha, y r3 hay& graze 50 ha) used to make hay (total of three mows- 190 t ha^{-1})
- Permanent pasture 119 ha

Livestock
- 200 beef cattle. Housed 5 months. Fed on farm grown straw/hay/grass.
- Producing 580 tonnes of FYM per year.
-

Energy use
- Grain dryer- 20,000 kWh yr^{-1} (72GJ) electricity & 10,000 l diesel
- Cultivator (3 yr^{-1} for each cereal/bean crop)
- Drill (1/yr for each cereal/bean crop)
- (Total for 3 cultivator and 1 drill = 28 l ha^{-1})
- Mow (3 yr^{-1} Clover pastures)
- Turn crop (4 yr^{-1})
- Green manure (estimate 1 drill)
- Estimated about 20,000 l diesel per year imported.

Manure/ nutrient management
- FYM piled outside in heaps.
- FYM applied to clover pastures by tractor and spiller
- Straw from cereals left on fields (except wheat-baled and used on farm)
- Clover/beans used to build soil fertility- no additional fertiliser added

Rotation: Clover pastures (3 yrs)- wheat (1 yr)- wheat/beans (1 yr)- green manure (1 yr)- wheat (1 yr)- beans(1 yr)- spring barley (1 yr).

Total carbon emissions from grain drying and crop and livestock production estimated at 105 tonnes CO_2 equiv.

***This does not include emissions from manure management and enteric sources.**

Feedstock options

I have described 4 different feedstock options potentially available for your farm so that you can compare between gas productions. Below in table 1-3, I have modelled the potential biogas/ methane potentials, and the energy (electricity and heat) required for each digester.

Feedstock type 1. Putting all FYM into a concrete anaerobic digester heated to 35ºC.

Feedstock type 2. As above but with the additional import of 200 tonnes of FYM (TS 25%).

Feedstock type 3. As feedstock 1 but with the additional import of 200 tonnes of dairy slurry (TS 9%)

Feedstock type 4. As feedstock 3 but including feeding digester with 2.3 tFM ha^{-1} (total 78.2 tonnes) of your Triticale straw rather than leaving on the field.

Comparison of Scenarios

Figure 1 contains six options generated from the table. The option details are below. For comparison, all of the values have been converted into kWh yr^{-1}. I have included a bar to represent net energy, which is the sum of all energy used and produced. As this is across all energy types used (i.e. diesel, electricity, biogas, methane, heat, etc) it may not truly represent total energy usage on your farm. Energy values for each energy type are included on the figure.

1. Baseline- Your current energy use. Assuming grain drying and crop production vehicles use diesel oil.

2. AD no CHP- Your current available farm feedstock (580t FYM) into an anaerobic digester (details in table 1 below), with no CHP unit. All electricity and heat is sources from the National Grid. Usable gas produced is in the form of biogas*.

3. AD and slurry, no CHP- Your current feedstock available plus an additional 200tonnes of dairy slurry. Again, details of anaerobic digester are in table 1, and usable gas produced is in the form of biogas*.

4. (3) with CHP- Feedstock as in 3 above, but with a CHP unit available. All usable gas is converted into heat and electricity.

5. CHP and comp/upgrade- Here 4 above with CHP using only enough gas to power the anaerobic digester (electricity only, not heat- it would make more sense to use your gas too for heat, and I'll look into this further- currently this is a restriction in our model which needs to be modified). All remaining gas is upgraded and compressed. Usable gas produced is in the form of methane.

6. (5) with no CHP- As 4 above, but without a CHP unit. All energy for electricity and heat to run anaerobic digester is sourced from the National Grid. All usable gas is in the form of methane.

*Please note, biogas cannot be stored very long in the form of biogas alone due to the quantity produced. Further treatment is required, for example, flaring, burning or compressing and converting into biomethane.

Table 1. Details of energy and heat required, and biogas, methane and digestate production for each feedstock type. This hopefully demonstrates the gas potential for each feedstock in the quantity available to you.

Feedstock	AD size required (m^3)	Biogas production ($m^3\ yr^{-1}$)	Retention time (days)	Electricity required ($kWh\ yr^{-1}$)	Heat required ($kWh\ yr^{-1}$)	Digestate (tonnes)	Methane production ($m^3\ yr^{-1}$)	Rate of feedstock ($Kg\ day^{-1}$)	Carbon emissions (Tonnes $CO_{2\ equiv.}$)
1	117	37038	67	5361	45036	540	22223	315	116
2	158	49705	67	7194	57048	725	29823	426	119
3	133	41644	56	7194	53445	734	24987	324	118
4	198	61767	76	7911	64836	787	36054	480	121

Table 2. Details of AD requirements with a CHP unit included. Here, all biogas produced is used in the CHP to produce heat and electricity. The surplus electricity and heat are minus that which is needed to run the digester. The values in the brackets are the additional potential carbon emissions available for you to save if you were able to use the energy produced on your farm, and therefore reduce sourcing it from the National Grid.

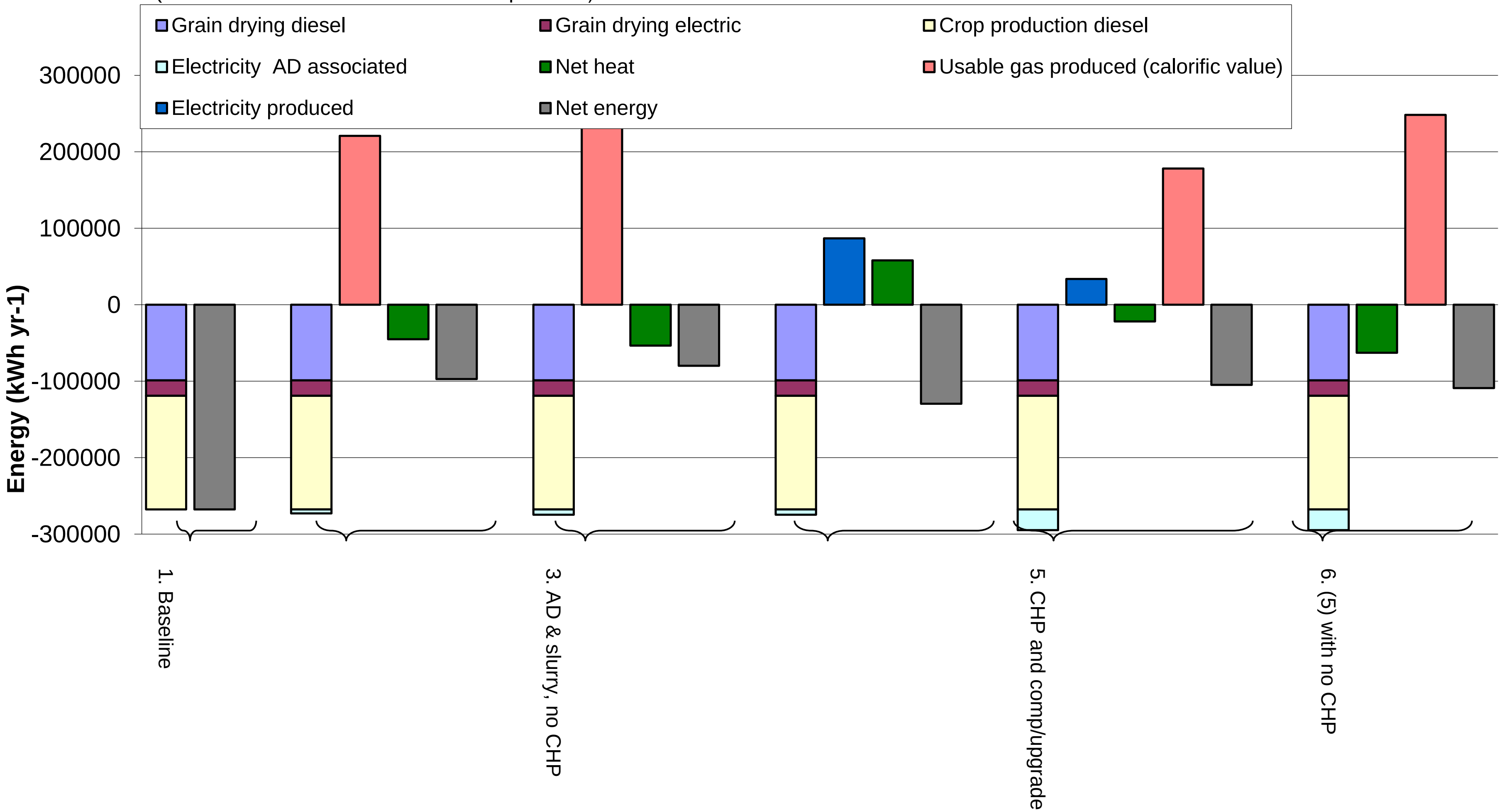
Feedstock	Electricity produced ($kWh\ yr^{-1}$)	Surplus electricity ($kWh\ yr^{-1}$)	Heat produced ($kWh\ yr^{-1}$)	Surplus heat ($kWh\ yr^{-1}$)	Carbon emissions (Tonnes $CO_{2\ equiv.}$)	kW generator required
1	77397	72036	110567	53734	105 (36)	9
2	103866	96672	148380	74890	105 (48)	12
3	87023	79829	124319	58114	105 (40)	10
4	125568	117657	179383	93926	105 (58)	15

Table 3. AD unit with and without CHP unit, for methane gas upgrade and compression. CHP unit runs only to provide enough to power the AD unit, then the remaining gas produced is left to be upgraded / compressed. Both with and without a CHP unit, there is a high demand for heat. Heat used here is in the form

of natural gas. If the energy produced is used on the farm, and not sourced from the National grid, there is an additional saving of tonnes of CO2 equiv. (value in the brackets = additional saving).

Feedstock	No CHP unit					CHP and Upgrade			CHP and Upgrade and compressed		
	Methane (m^3)	Energy required (**Upgrade**) (kWh yr^{-1})	Energy required (**compressed**) (kWh yr^{-1})	Heat required (kWh yr^{-1})	Tonnes $CO_{2\ equiv.}$	Upgraded Methane (m^3)	Heat required (kWh yr^{-1})	Tonnes $CO_{2\ equiv.}$	Compressed & upgraded Methane (m^3)	Heat required (kWh yr^{-1})	Tonnes $CO_{2\ equiv.}$
1	22223	16472	23139	53056	116 (52)	17699	26667	111 (41)	16170	17778	109 (38)
2	29823	22111	31056	67223	119 (69)	23752	31667	112 (55)	21699	19722	109 (50)
3	24987	19472	27195	62778	118 (58)	19613	31667	112 (46)	17918	21667	110 (42)
4	36054	26445	37250	76390	121 (84)	28773	33889	121 (67)	26286	19167	109 (61)

Figure 1. Please see above for details of each scenario. Values are calculated to a standard value (kWh yr $^{-1}$). Diesel = 12 kWh l^{-1}, biogas = 5.96 kWh $m^{3\,-1}$, methane = 9.94 kWh $m^{3\,-1}$. Values from Greenstone.org (online reference below). Although scenario's 2 and 3 produce a high volume of gas, it is less suitable for certain uses (as it has not been scrubbed or compressed) than scenario's 5 and 6.



Summary

As you can see, from the tables and figures, there appears to be an opportunity to reduce the requirement of importing energy onto your farm (as well as reduce your CO_2 equiv. emission). However, the values calculated consider the energy generation of the AD produced at a low, steady rate throughout the year (with feedstock added and removed frequently). Due to the nature of your farming practice, I understand this would not be feasible. This is in respect to the feedstock availability being limited to when sheds are emptied. Even if feedstock was stored outside and the AD unit fed regularly, due to the ageing of the manure, the biogas potential would reduce over time. Also, I expect the electricity requirements for your grain drying will be greater than that the AD unit can produce at the modelled rate. As our model only calculates for a continuously fed AD unit, I would like to look into the option of alternative digester types, for example, batch digester systems. This is where all the feedstock is put into an AD unit, left to digest over a number of months without additional stock being provided. Gas here will be continuously produced (at a high rate initially, then slower towards the end of the retention period), and the digestate being available in a large quantity in one go at the end of the process.

Equally, I would like to look further into the practicality of biogas compression for the batch system, and its use for agriculture vehicles. I am currently waiting to discuss this with a researcher external to the university. As soon as I have spoken to them, I'll let you know the outcome. The volume of gas presented in the tables above show the maximum available calorific value for the gas. Total energy output may be much reduced if used in equipment with low efficiency. This means 100kWh of methane will not produce 100kWh of electricity.

Overall, your case has been very interesting into considering the requirements of the farm to match that which the AD unit can (or cannot) provide. Although the numbers appear to look great, this report has not produced a clear outcome with regards AD suitability for your farm, and has in fact, raised a lot of questions. Thank you again for allowing me to use your farm as a case study and I'll keep you informed of the outcome of the next stage.

Reference for calorific values:
http://www.greenstone.org/greenstone3/nzdl%3Bjsessionid=D29D761C911D8722DE9E044D159BF2C7?a=d&d=HASH01684ae27681e761ec29766d.9&c=hdl&sib=1&dt=&ec=&et=&p.a=b&p.s=ClassifierBrowse&p.sa

UNIVERSITY OF Southampton
School of Biological Sciences

Initial Evaluation of RELU Organic AD Model data for xxxxxxxx xxxxxxxxx Farm, Mere

21st February 2011

Laura Clements

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*** Please note; the information contained within this report are estimates using our independently developed AD tool and should not be used alone to make decisions on AD requirements for your farming system. Always consult a specialist regarding actual dimensions and gas production.**

Current practice- no AD unit

Summary
- 70 Friesian dairy cows, housed approximately 50% of the time (13tonnes slurry/cow)
- 42 followers, housed approximately 33% of the time (6 tonnes FYM/cow)
- 1000m³ waste/wash water collected from dairy/barn/yard
- 101 ha permanent grass

Of that: 50 ha grass for grazing (11.2 t/ha)
51 ha grass for clamp silage (mown 1 - 4 times/yr) (11.2t/ha)

Electricity use on farm

Table 1. Electricity consumption for the dairy parlour per year. Total electricity use over one year = 63.4 GJ, which is between **8698 - 8756 kg $CO_{2\ equ}$**.
[1] Assumption lights on for 3 hours a day, every day.

Equipment	Daily Use (hr/day)	Weekly use (days/wk)	Energy required (kW)	Energy used per week (kWh/wk)	Energy used per year (kWh/yr)	Energy used (GJ/yr)
Vacuum pump	3	7	3.0	63.0	3285.0	11.8
Compressor	5	7	4.0	140.0	7300.0	26.3
Washers	5	7	3.0	105.0	5475.0	19.7
Lights	3[1]	7	0.5	10.5	547.5	2.0
Space heater	[2]Current yr's use of 100l diesel at 36.4MJ/l =					3.6
Total			**10.5**	**308.0**	**16607.7**	**63.4**

[2] Average diesel use for space heater 20 l/ yr = 0.72 GJ.

Table 2. Electricity consumption for a milk delivery enterprise per year. Total electricity use over one year = 52.0 GJ, which is between **7179-7881 kg $CO_{2\ equ}$.**

Equipment	Daily Use (hr/day)	Weekly use (days/wk)	Energy required (kW)	Energy used per week (kWh/wk)	Energy used per year (kWh/yr)	Energy used (GJ/yr)
Milk float	4	7	2.2	61.6	3212.0	11.6
Pasteuriser	6	2	8.0	96.0	5005.7	18.0
Separator	3	2	2.0	12.0	625.7	2.3
Lights	5[1]	2	0.5	5.0	260.7	0.9
Compressor	5	2	3.0	30.0	1564.3	5.6
Cold store	3	7	2.0	42.0	2190.0	7.9
Heater	4	2	3.0	24.0	1251.4	4.5
Pump	1.5	2	2.2	6.6	344.1	1.2
Total				**277.2**	**14453.0**	**52.0**

[1] Assumption lights on for 5 hours a day (at 2 days a week).

Fossil fuel use:
Total fossil fuel use was provided at 3800 l diesel per year. This equates to 215 GJ energy, which is between **12154- 12656 Kg $CO_{2\ equ}$**.

Available material back to field: 596 tonnes (this includes straw import) or 1596 tonnes when including waste water.

Total emissions of parlour, crop production and delivery enterprise between 28533 - 28801 kg $CO_{2\ equ}$. or 28.5 - 28.8 tonnes $CO_{2\ equ}$

*** This does not include emissions from manure management and enteric sources.**

Alternative options- including an anaerobic digester

I have included 5 scenarios below so you can compare between options. Scenarios 1 & 2 are current practice and differ between the inclusion of wastewater into the digester. As anaerobic digesters produce more biogas when slurry is co-digested with other material, for example plant waste, I have included scenario 3 and 4 which consider the availability of poultry waste for digestion, and scenario 5 which diverts 23 tonnes of grass silage from animal feed to digester feedstock. All scenarios assume the digester is set to 35ºC. Data shown represents average production over one year, with biogas values based on those given in the literature. These values are examples of what may be achieved assuming optimal operation of the digester~~.~~

Scenario 1. Current practice- with AD unit (no waste water)
Putting all slurry and FYM: Load into digester at 3kg/m^3/day.

Scenario 2. Current practice- with AD unit (inc. 1000 tonnes waste water)
Putting all slurry FYM- inc. 1000 tonnes of waste water. Load into digester at 1kg/m^3/day.

Scenario 3. Including 100 tonnes of poultry broiler waste.
Scenario 2 plus 100 tonnes of poultry broiler waste. Load into digester at 2kg/m^3/day

Scenario 4. Including 100 tonnes of poultry layer waste.
Scenario 2 plus 100 tonnes of poultry layer waste. Load 2kg/m^3/day

Scenario 5. Including 23 tonnes silage deviated from animal to AD.
Scenario 3 (poultry broiler waste) with 5ha worth of silage (3 cut) = 57.5 tonnes diverted from animal feed to digester. Load into digester at 2kg/m^3/day.

Table 3. Details of Anaerobic digester for each scenario. Calorific value of biogas = 6kWh/m^3. Retention time is the average number of days material should remain in the digester.

Scenario	AD size required (m^3)	Biogas production m^3/yr	Methane production m^3/yr	Retention time days	Electricity required (GJ)	Heat required (GJ)	Digestate (tonnes)	Carbon emissions (tonnes $CO_{2\ equ.}$)
1	55	17,147	10,288	33	18	121	539	39
2	118	17,147	10,288	25	51	270	1539	54
3	125	39,647	23,788	25	55	285	1612	55
4	125	28,397	17,600	25	55	285	1627	55
5	166	45645	27087	32	57	313	1662	57

You have three main options on how to use the biogas produced:

1) Export of the gas as biogas- potentially for boiler use. Alternatively export to the national grid to claim FIT's (feed in tariffs). Here, electricity and heat are imported from the National Grid to power AD unit and so results in high $CO_{2\ equ.}$ emissions.

2) Use a combined heat and power unit (CHP) to generate both heat and electricity. From this, the model uses the heat and electricity generated to power the AD unit. Where there is insufficient heat or electricity generated from the anaerobic digester, the difference is made up with fossil fuelled derived sources of power (import will be greater than simply making up the difference). Excess electricity or heat can be used elsewhere on the farm.

3) Use a CHP unit (to power AD unit), and with the remaining biogas, compress and upgrade to biomethane to use in vehicles designed to run on compressed natural gas.

Table 3 shows some of the potential values for heat and electricity. In this case it is assumed that the CHP unit produces electricity with a 35% efficiency and that all of the available heat can be captured. This will depend on the type of CHP unit and heat capture fitted. It is assumed that the biogas will be primarily used to fuel/ heat AD with surplus after. The value for the generator given is that which could operate continuously on the biogas produced. If the biogas is stored then it would be possible to operate a larger capacity generator for shorter periods.

Table 4. Results of each Scenario output when using the biogas produced to fuel a CHP unit.

Scenario	Electricity produced (GJ)	Surplus electricity (GJ)	Heat produced (GJ)	Surplus heat (GJ)	Whole operation tonnes $CO_{2\ equ}$	kW generator required
1	129	111	184	73	13	4
2	129	78	184	-86 (101)	24	4
3	298	243	426	141	13	10
4	221	166	315	30	13	7
5	340	283	485	172	13	11

* Values in brackets are the recommended GJ required to make up the difference needed to be imported.

The electricity surplus for scenario 1 is 111GJ. This is around 96.5% of the electricity used on your farm for parlour and milk delivery. Scenario 2 produces only around 67.8% of the electricity used on your farm. This is because as water content increases, volume required increases, and the more electricity and heat is required to power the AD unit.

As you can see- broiler poultry (scenario 3) manure can increase your gas output, and in turn, your surplus electrical available to 298 GJ and heat surplus to 141 GJ. Both of which will fully power and heat the farm and probably the home too.

I have plotted the details from table 4 below to show you your best/ worst case scenario's easier (figure 1). Although scenario 3 produces the most energy, it also requires a larger amount of energy input and requires a digester of twice the capacity, compared with scenario 1. Scenario 3 and 5 differ by the addition of 57.5 tonnes of grass silage in scenario 5, while scenario 3 and 4 differ between the type of poultry waste used.

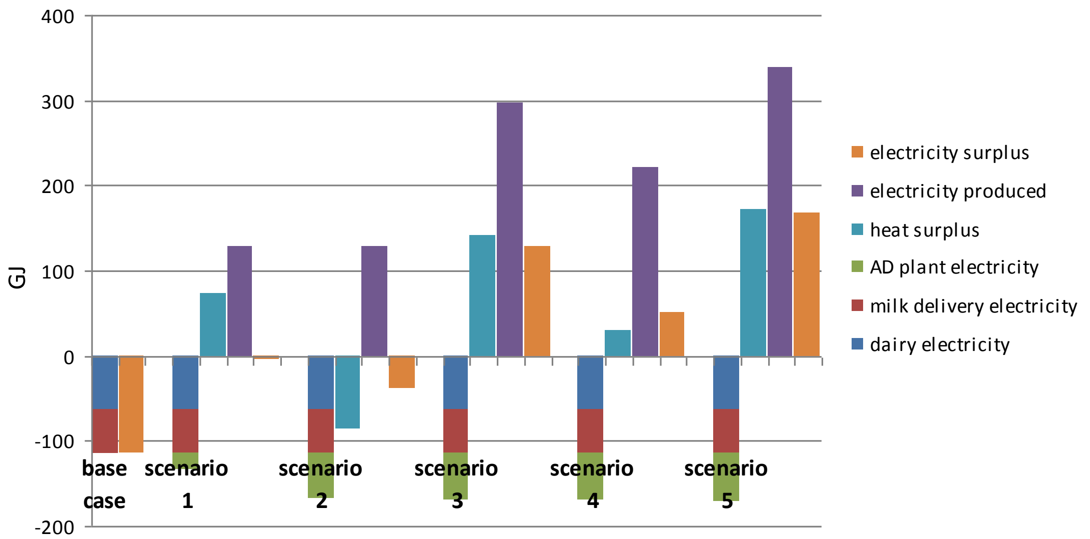

Figure 1. Total energy generation (as electricity and heat) for each scenario using a CHP unit. The total electricity cost is seen in the first bar of each scenario and is made up of milk delivery, dairy and AD plant electricity use. The blue bar represents heat surplus. Were negative, heat needs to be imported. The purple bar represents total electricity produced, and the orange bar is the net electricity after the electricity cost have been deducted.

I have also included the details for if you were to consider upgrading and compressing your biogas to use/ sell as a biofuel (Table 5). These also consider the system using a CHP unit to primarily power the AD plant. There is no carbon benefit in CHP with upgrade and compressing of biogas due to the large heat energy demand in all scenarios compared with your existing practices.

Table 5. Upgrading and compressing biogas for vehicle use *Values in brackets= the recommended GJ required to make up the difference.

Scenario	Compressed methane (m^3)	Electricity produced (GJ)	Surplus electricity (GJ)	heat produced (GJ)	Surplus heat (GJ)	Whole operation tonnes $CO_{2\ equ}$	kW generator required
1	6888	42	0	61	-51 (59)	32	1
2	4823	68	0	98	-173 (203)	40	2
3	15172	108	0	285	-132 (155)	37	4
4	10390	90	0	129	-157 (184)	39	3
5	17601	119	63	169	-144 (169)	38	4

Wir geben BioGas. EnviTec Biogas.

Project: BGP Example Date: 20.11.2012
Offer number: 12 - xxxxxxx Initial startup: 2013

Economics calculation for your biogas plant Großbritanien

(Short version)
Investment net
Offer EnviTec Biogas: 1.973.300,00 €
Grid-Connection (estimated cost): 70.000,00 €
Services by customer: 216.000,00 €
Land costs: 0,00 €
Technical building: 120.000,00 €
Earthworks: 24.000,00 €
Road works: 24.000,00 €
Authorisation: 19.000,00 €
Others: 29.000,00 €
Silage plate (estimated cost): 240.000,00 €
Unforseen events approximately 1,5% of the investment: 37.489,50 €
Total invest: 2.536.789,50 €
Personal capital: 0% - €
Subsidies: 0% - €
Need for financing: 2.536.789,50 €
Income net
Electrical output CHP I: 3.915.903 kWh 0,21 € / kWh 822.339,53 €
Total electrical output: 3.915.903 kWh 0,21 € / kWh 822.339,53 €
CHP I (heat usage 0%): 0 kWh 0,02 € / kWh - €
Total thermal output: 0 kWh 0 € / kWh - €
Other incomes:
Sales of fertilizer 6.183 t/a 6 € / t 37.097,90 €
Total other incomes: 37.097,90 €
Total Income: 859.437,42 €
Estimate costs net
Linear depreciation costs for machines p.a.: depreciation period: 10 years 133.100,14 €
Linear depreciation costs for premises p.a.: 15 years 80.385,87 €
Interest rate of half value as new: 6,50% 82.445,66 €
Purchase of corn silage: 8.350 t / a 25,0 € / t 208.750,00 €
Purchase of EnVital: no 5.675 kg / a 2,3 € / kg - €
Transport of residue: 6.183 m³/a 1,0 € / m³ 6.182,98 €
Costs for the use of water: 200 m³ or t 0,0 € / m³ - €
Energy costs: approx. 8% of the created electrical energy: 0,12 € / kWh 313.272 kWh/a 37.600,00 €
Staff costs: 18,5 € / h 5,0 h/d 33.800,00 €
Biological support: 1.000 € / months 12 months 12.000,00 €
Insurance cover: 700 € / months 12 months 8.400,00 €
Estimated costs – service on demand for CHP: 0,017 € / kWh 66.570,34 €
Estimated costs – service on demand for the rest of the plant: 0,008 € / kWh 31.327,22 €
Cost: 700.562,22 €
Profit per year in € : 158.875,20 €
Profit per month in € : 13.239,60 €
The attached profitability calculation is a non-binding sample calculation (example) and shall neither be part of the contract nor shall it serve as a basis for any claims. We point out that the actual costs and profitability of the biogas plant is determined substantially by factors we cannot influence, as for example but not limited to the operational mode, the quality of the input or the legal framework conditions. In this context we are in particular not liable for a certain remuneration of the produced electricity.