Impacts of bioenergy maize cultivation on agricultural land rental prices and the environment

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Executive summary

In 2014 the area of maize grown was estimated at 171,000 hectares in England (Defra, 2014) and 9,300 hectares in Wales (Welsh Government, 2015). Maize is mainly grown for livestock feed but is increasingly grown as a feedstock for anaerobic digestion (AD) biogas production (29,000 hectares in England in 2014) and research suggests that bioenergy cropping for AD could increase to between 200,000 and 300,000 hectares. Despite this relatively small scale, concerns have been raised over local impacts on agricultural land rental values and the environment. This study has reviewed the available evidence on both these issues.

Land rental value impacts

A temporal trend analysis of land rental data in England identified that rental values under Full Agricultural Tenancy (FAT) agreements increased regularly between 2001 and 2012, from a low base, whereas Farm Business Tenancy (FBT) rental values were more variable, with prices falling until 2006 and rising thereafter. Spatial modelling of land rental values found no significant influence of proximity to AD plants. As the emergence of AD plants is relatively recent, it is likely that their influence is not fully represented within the most recent set of rental data and it is recommended that the analysis is repeated when the sector has developed further and more evidence is available.

The evidence from four AD plant case studies also captures the broad trend of rising land rental values over the past decade or so but was inconclusive in the attribution of effects from a growing AD sector. Thus in a period of increasing pressures on land use from a range of drivers – agriculture, renewable energy and development - interviewees found it difficult to comment on the extent of the impact of AD. In particular, they pointed to the role of fluctuating returns from agricultural commodities, due to a combination of volatile global markets and changing policy priorities. In summary, while anecdotal evidence suggests a localised increase in land rental values where there is a concentration of AD plants using maize for feedstock, we are not able to confirm this from the data with any statistical certainty.

Environmental impacts of growing maize for AD

A review of research on the environmental impacts of maize production indicates that the magnitude of surface runoff, sediment, phosphorus (P) and nitrate (NO_3) losses to water from maize cropped land are within the range of those reported for other tillage crops. However, soil surveys have shown that maize and other late harvested crops, such as potatoes, show more signs of soil degradation due to trafficking during harvest operations, etc., when soils are wet, than winter cereals and grass crops. As such the net environmental impact of maize will depend on which crops are displaced. June Agricultural Survey data analysis suggests that most crops are displaced in direct relation to their area. However, wheat in arable systems and permanent grazing in livestock systems are less likely to be displaced than other crops, but due to a small sample size, these results must be treated with caution.

An assessment of which crops are likely to be displaced by AD maize was used to model the potential environmental impacts of scale of AD maize area by water management catchment (WMC). The environmental impact of moving from one hectare of each of the crop categories to one hectare of maize was calculated using the ADAS Farmscoper and AHDB EAgRET tools and scaled based on crop displacement in each WMC. For arable dominated WMCs, the modelling tools predicted increases in nitrate, phosphorus and sediment loss associated with an increased area of maize production. In contrast to nitrate, phosphorus and sediment, emissions of total carbon dioxide, ammonia and nitrous oxide decreased with additional maize area and soil carbon was reduced. For grassland dominated WMCs, the models predicted increased losses of nitrate, phosphorus and sediment, but also an increase in the emissions of total carbon dioxide, nitrous oxide and ammonia. The losses of nitrate,

phosphorus and sediment were more than 5 times higher when grassland was displaced rather than an arable crop. It should be noted that the results described above are based on models that do not account for local conditions and management practices that would affect the environmental impact of the crops. It was also assumed that digestate is not recycled to land.

Recycling digestate would potentially increase NH_3-emissions from application relative to baseline scenarios. However, the nutrients supplied by digestate will displace the need for manufactured fertiliser (N, P, K and S) applications to meet optimal crop nutrient requirements and consequently the environmental impacts associated with manufactured fertiliser production (e.g. energy use, the use of fossil fuels and finite raw materials such as rock phosphate) will be reduced. Nutrient planning by farmers is important to maximise the nutrient use efficiency of digestate applications and minimise the risks of nitrogen and phosphorus losses to the environment

An analysis of the potential water quality impacts of the predicted changes in nitrate and phosphorus losses at the WMC level suggested that there was unlikely to be any impact on drinking water quality for nitrate. For phosphorus, the situation was much more complex, with impacts being dependent on the spatial placement of the additional maize area, suggesting that the impact on water quality is likely to be localised. It should be noted that this analysis looked only at two scenarios that effectively represent upper and lower bounds in terms of the potential impacts on water quality. A more detailed analysis would be required to draw firm conclusions on the impacts of the production of additional maize for AD on water quality at waterbody level.

Potential mitigation strategies for reducing the environmental impact of maize cropping involve i) cover cropping or ii) soil management techniques. The available evidence shows that cover crops sown post maize harvest do not establish well and do not significantly reduce diffuse water pollution; oversowing can establish a cover crop successfully but may reduce yield. Before over-sowing can be effectively implemented, further research is required to develop: 1) oversowing methods that are effective in establishing ground cover without reducing maize yields or quality and 2) cover crop destruction techniques to avoid negative impacts on subsequent crop yields or quality. In terms of soil management, studies found that neither non-inversion nor strip-tillage cultivation demonstrated any significant impacts in reducing diffuse water pollution. When soil conditions are appropriate, chisel ploughing post maize harvest can be effective at reducing surface runoff and sediment losses.

The four case studies have highlighted significant variation in the environmental impact of maize cropping for AD according to scale, location and management. Environmental impacts are largely associated with regional differences, particularly in soil type, slope and rainfall. While there is widespread recognition of risks to soil and water, the case studies illustrated that maize grown in rotation on suitable land and managed well are unlikely to have greater environmental impacts than displaced cropping. However, there were concerns over the extent to which sector growth and associated land availability issues might lead to greater environmental risks in future years.

Environmental impacts of the AD process

The most significant environmental impacts from the AD process, relative to growing maize as a feed for livestock, are likely to be emissions of methane during biogas production, emissions of methane and ammonia from digestate storage and ammonia emissions following application of the digestate. Methane emissions will be lower in a well-designed and managed AD process, as the fugitive emissions in the plant will be lower and the digestion process more complete than on livestock production systems. Ammonia losses following the application of crop-based digestate have been shown to be greater than following cattle slurry. This is consistent with the results from the *DC-Agri* project which concluded that the ammonia emissions following food-based digestate applications were greater than from livestock slurry, which reflected the higher pH of the food-based digestate.

Further information is required to develop innovative management strategies to reduce nitrogen (N) losses (e.g. acidification, separation of solid and liquid fractions) to increase N (and P) nutrient use efficiencies (NUE) of the range of digestates from the anaerobic digestion of different feedstocks (food, manure and crop-based). This information is crucial to support improved advice to farmers on how to maximise NUE and to minimise agriculture's environmental footprint, and the development of sustainable intensification of agricultural systems and closed-loop nutrient systems.

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1 Introduction

Anaerobic Digestion

Anaerobic digestion (AD) is the process of transforming organic matter into biogas in the absence of oxygen. In an agricultural AD plant farm produce and/or waste is converted into biogas and (liquid and solid) digestate. Commonly this biogas is then converted into heat and electricity through a cogeneration heat and power (CHP) system, where the electricity can be used or sold to the National Grid. Other AD plants convert biogas into bio-methane which is then sold to the Grid (BtG).

Anaerobic digestion of farm manures and slurries can reduce greenhouse gas emissions but due to the low biogas production potential of these feedstocks it is generally thought that co-digestion with food waste or purpose grown crops, such as maize, is required to maximise energy output of such systems (NNFCC, 2013). The liquid part of the digestate is nitrogen rich and is used as a fertiliser while the solid digestate can be utilised as a compost or soil conditioner. As such, AD can avoid the greenhouse gas emissions associated with fertiliser manufacture and improve nutrient management on farms.

The Feed-in Tariff (FIT) scheme[1] is a government programme designed to promote the uptake of a range of small-scale renewable and low-carbon electricity generation technologies by requiring electricity suppliers to make tariff payments to generators. AD plants can currently receive subsidies from the Feed-in Tariff (FiT) scheme which equate to 12.46 pence per KWh of electricity generated under 250kW, 11.52 pence per kWh between 250 and 500kW and 9.49 pence for 500kW and above. A lesser utilised subsidy is the Renewable Heat Incentive (RHI) where AD plants up to 200kW can receive 7.5 pence per kWh. These incentives have encouraged the growth of crops for bioenergy, such as maize for anaerobic digestion (AD) in recent years. The number of agricultural-fed AD plants has increased six-fold in just 4 years[2] with 139 from a total of 218 AD plants currently operational in England and Wales using feedstocks from agriculture (Table 1-1).

Table 1-1: AD plants in the England and Wales

Type of AD plant	Number of AD plants currently in England	Number of AD plants currently in Wales
Agricultural	134	5
Waste-fed	73	6
Total	**207**	**11**

Source: http://www.biogas-info.co.uk/resources/biogas-map/

The impacts of land use change has become increasingly of interest to policymakers within the last decade and land planning of rural areas has increased (Rudel and Meyfroidt, 2014). The main pressures on land include providing greater food and energy security, increasing woodland coverage and offering better environmental protection (CISL, 2014). This raises issues of trade-offs between these priorities and the role of government support, for example through agricultural productivity grants, agri-environmental schemes and renewable energy subsidies.

There is growing anecdotal evidence that maize is impacting on land rental prices in England and Wales and displacing cash crop production such as potatoes and maize traditionally used as feed. Concerns have also been raised that an increase in maize production for AD may contribute to poor water quality

[1] https://www.ofgem.gov.uk/environmental-programmes/feed-tariff-fit-scheme
[2] http://www.biogas-info.co.uk/resources/biogas-map/ accessed 09/11/2015

and flooding. It is therefore important to understand the impacts of continued support for agricultural AD. This project considers the evidence of a link between maize for AD and land rental prices and builds on previous Defra funded research on the environmental impacts of maize[3] to consider the environmental and economic consequences of an increase in maize production in England and Wales.

Methodology

Defra statistics and other data sources were analysed to establish recent trends in agricultural land rental prices. Statistical analysis was undertaken and growth trends identified over a ten year period for full agricultural tenancies (FAT), farm business tenancies (FBT) and seasonal agreements. These were analysed against a set of variables to test for correlation. To test the hypothesis that bioenergy cropping for AD is impacting land rental prices, a statistical modelling approach (with a spatial element) was undertaken.

For the environmental analysis, a review was undertaken of recent UK research on the impacts of maize production on diffuse water pollution, soil quality and biodiversity. The review also included the role of mitigation strategies. As the net impact of growing maize relies heavily on the land use it displaces, an analysis of the June Agricultural Survey data was used to identify which farm activities are being displaced by maize being grown for anaerobic digestion. This analysis then considered a range of expansion scenarios in Water Framework Directive Water Management Catchments.

Additionally, qualitative evidence on land rental values and crops displaced as well as evidence on economic, environmental and social impacts was gathered using four case studies of AD plants. These case studies were selected on the basis of scale and feedstocks used and included two crop only digesters of at least 1 MW in size, one mixed agricultural feedstock digester of at least 140 kW in size and one small scale mixed agricultural feedstock digester <80 kW in size. Evidence was based on interviews with the plant owner, supplying farmers, intermediaries and relevant stakeholders such as land agents, the Environment Agency and the NFU.

Report structure

In **chapter 2** we focus on general trends in agricultural land rental prices, including a trend analysis of agricultural land rental prices and testing the hypothesis that bioenergy cropping for AD is impacting land rental prices in England & Wales, using spatial regression modelling.

Chapter 3 focuses on the environmental impacts of growing maize and endeavours to quantify the environmental footprint of maize production. This considers the direct and indirect environmental impacts of maize production as well as mitigation strategies.

In **Chapter 4**, we consider the evidence for preferential displacement of crops by maize being grown for anaerobic digestion through analysing the June Agricultural Survey and estimate the direct (and indirect) impacts of such land use change, notably on water quality.

Chapter 5 sets out the evidence from the four AD plant case studies across the range of economic and environmental issues. These provide both qualitative and quantitative data to understand the impacts of bioenergy maize cultivation on agricultural sector and the environment.

[3] WQ0140, Minimising the environmental impacts of maize cultivation; AR0412, Modifying weed management in a broad row crop (maize) for environmental benefit; SP0404, Soil erosion control in maize.

2 Impacts of bioenergy maize on agricultural land rental prices

2.1 Maize cropping

Agriculture accounts for around 70% of land use in the UK. In England, it is dominated by commodity food crops and grassland is but is dynamic over time at a local scale. Maize is mainly grown as a fodder crop and in total represents only 4% of all arable crops or 3.5% of total croppable land (Defra, 2014). Maize for anaerobic digestion (AD) was captured as a separate category in 2014 (Table 2-1).

Table 2-1 Arable crops on commercial agricultural holdings on 1 June 2014, England

Thousand hectares

	2012	2013	2014	% change 2014-13	June 2014 confidence interval	Indicator
Total arable crops	**3 887**	**3 820**	**3 870**	**1.3**	**+/- 35**	✓✓✓
Cereals	**2 594**	**2 492**	**2 634**	**5.7**	**+/- 29**	✓✓✓
Wheat	1 656	1 505	1 797	19.4	+/- 25	✓✓✓
Barley	623	828	709	-14.4	+/- 14	✓✓✓
winter	329	257	363	41.4	+/- 11	✓✓✓
spring	294	571	345	-39.5	+/- 9	✓✓✓
Oats	92	138	105	-24.3	+/- 6	✓✓
Rye, mixed corn and triticale	23	22	24	11.8	+/- 3	✓
Oilseed crops	**742**	**714**	**648**	**-9.1**	**+/- 16**	✓✓✓
Oilseed rape	713	676	632	-6.6	+/- 16	✓✓✓
winter	702	584	618	5.9	+/- 16	✓✓✓
spring	11	92	13	-85.5	+/- 3	☒
Linseed	29	34	15	-57.9	+/- 2	✓
Borage	1	3	2	-18.2	+/- 1	☒
Potatoes	**112**	**103**	**105**	**1.7**	**+/- 4**	✓✓✓
Early crop (harvested on or before 31 July)	11	11	10	-4.9	+/- 1	✓
Main crop (harvested after 31 July)	101	92	95	2.5	+/- 4	✓✓✓
Other (non-horticultural) crops	**439**	**511**	**482**	**-5.6**	**+/- 11**	✓✓✓
Sugar beet [(a)]	120	117	116	-0.6	+/- 3	✓✓✓
Field beans	91	115	103	-10.0	+/- 6	✓✓
Peas for harvesting dry	24	28	31	8.0	+/- 4	✓
Maize [(b)]	143	182	171	-5.9	+/- 7	✓✓✓
- of which grain maize	9	11	7	-36.7	+/- 2	☒
- of which fodder maize	134	171	135	-21.1	+/- 5	✓✓✓
- of which maize for anaerobic digestion	nc	nc	29	na	+/- 4	✓
Root crops, brassicas and fodder beet for stock feeding	19	26	21	-18.3	+/- 2	✓✓
Leguminous forage crops	10	12	11	-4.1	+/- 1	✓
Other crops for stockfeeding	9	8	9	12.3	+/- 1	✓
All other arable crops	23	23	20	-15.9	+/- 2	✓
- of which short rotation coppice	3	3	3	7.5	+/- 0	✓✓
- of which miscanthus	8	7	7	-0.9	+/- 1	✓✓
- of which crops for aromatic or medicinal use	3	3	3	-4.6	+/- 1	☒

nc: not collected

na: not available

(a) Not for stockfeeding.

(b) Maize for anaerobic digestion was added as a new category in 2014. The percentage changes for grain maize and fodder maize should be treated with caution as maize for anaerobic digestions could have been classed as grain or fodder maize in 2013.

2.2 Land rental values in England

The 2014 June Agricultural Survey in England (Defra 2014) highlights the breakdown of rented land by tenure and indicates an incremental increase in more short-term arrangements, relative to Full Agricultural Tenancies (FATs) (Table 2-2).

Table 2-2 Areas of owned and rented land on commercial agricultural holdings on 1 June 2014, England

Thousand hectares

	2012	2013	2014	% change 2014-13	June 2014 confidence interval	Indicator
Land owned	**5 733**	**5 796**	**5 826**	**0.5**	**+/- 46**	✓✓✓
Land rented in for 1 year or more	**3 127**	**3 146**	**3 076**	**-2.2**	**+/- 41**	✓✓✓
Full Agricultural Tenancies	1 592	1 565	1 512	-3.4	+/- 24	✓✓✓
Farm Business Tenancies	1 084	1 123	1 120	-0.2	+/- 29	✓✓✓
Other agreements	450	458	443	-3.2	+/- 16	✓✓✓
Seasonally rented in land [a]	**497**	**499**	**506**	**1.3**	**+/- 14**	✓✓✓
Seasonally let out land [a]	**326**	**345**	**345**	**0.2**	**+/- 18**	✓✓

The latest published statistics on farm rents in England for 2013/14 (Defra 2015) indicate that between 2012 and 2013, the average rent for Full Agricultural Tenancies (FATs) increased by 5% to £171 per hectare; the average rent for Farm Business Tenancies (FBTs) increased by 11% to £196 per hectare; the average rent for seasonal agreements increased by 9% to £127 per hectare (Figure 2-1).

Trends in land rental prices should reflect to some extent the wider economic context for land use, notably return from agriculture. This is more complex because of the buffering effect of term lets and the agricultural cycle. Thus returns from agriculture may have both fallen and recovered again within the period of any farm FBT agreement, while farmers seeking land for cash crops or grazing through seasonal lets have made commitments to markets or have animals in the systems which limit their flexibility in responding to market price changes.

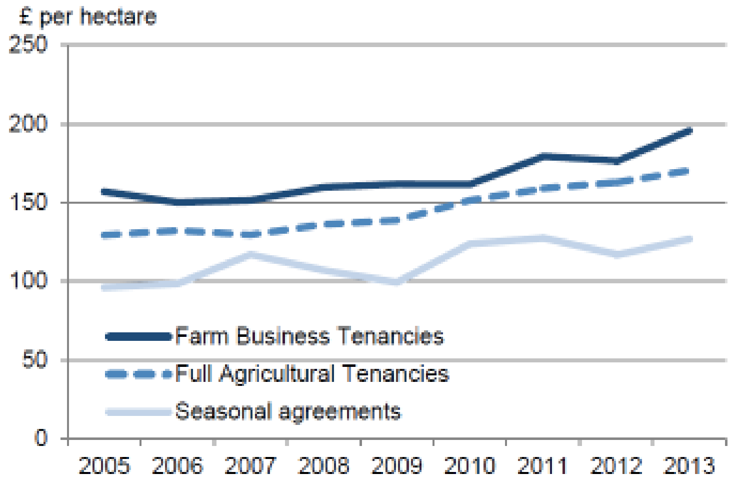

Figure 2-1 Average rents by agreement type: 2005 – 2013 (Defra 2015), England

Figure 2-2 highlights the fact that while agricultural incomes can vary significantly across years, the trend from 2005 to 2014 has been of rising incomes with modest year-to-year variance. This is in principle consistent with the steady increase in land rental values in Figure 2-1.

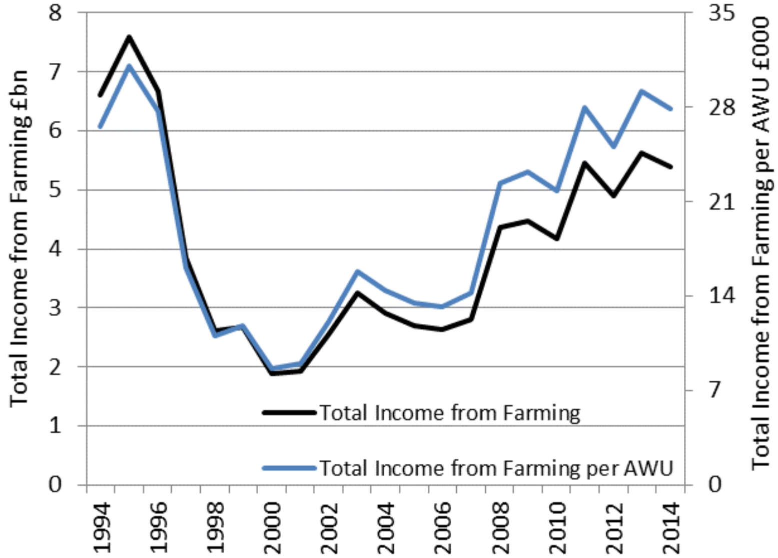

Figure 2-2: Agricultural industry income trends in the UK (in real terms) (Defra 2015)

The 2014 RICS/RAU Rural Land Market Survey results show that growth in demand for farmland purchase continues to outstrip that of supply (RICS, 2014). While rents are also rising, they are doing so at a slower pace than land prices so that yields for let land remain close to their all-time low of 1.7%. RICS surveyors estimated 2014 average annual arable land rents (under the Agricultural Tenancies Act) at £162 per acre, having increased by 6.1% over the year and pasture land rents at £104, having fallen by 5.1% over the previous twelve months. This raises the issue of changing land ownership and value driving rents as well as the commercial returns available from various land uses and the overall balance of supply and demand of rented land.

It is within this context that the assessment of the impact of land use for anaerobic digestion feedstocks, notably maize needs to be considered.

2.3 Trend analysis of agricultural land rental prices

A regression analysis was used to understand how knowledge-driven metrics of interest may affect the price per hectare of farmed land, as measured by Farm Business Survey (FBS) estimates of average annual rental rates for England, published in March 2014[4,5]. This analysis was based upon the cost of Full Agricultural Tenancy Agreements (also known as 1986 Act tenancies), which are those agreed before 1 September 1995, and Farm Business Tenancies, which are those agreed after 1 September 1995[5]. The original analysis also looked at the seasonal agreements, which displayed a trend comparable to the Full Agricultural Tenancy Agreements, masked by fluctuations restricting stability for further temporal analysis (Figure 2-3).

[4] Rental data have been sourced from the Farm Business Survey since 2004. Before this separate annual Tenanted Land Surveys were conducted by Defra. The last of these was undertaken in 2004. Note that there was no tenanted land survey in 2003, estimates for this year were calculated as the midpoints between 2002 and 2004

[5] www.gov.uk/agricultural-tenancies

The annual average prices per hectare under the Full Agricultural Tenancy (FAT) Agreements between 2001 and 2012 have generally increased over this period. Meanwhile, the average prices of Farm Business Tenancies (FBT) are more variable, with prices falling until 2006 and rising thereafter. The price for land under the Farm Business Tenancies are generally higher than those under the Full Agricultural Tenancies during the period.

Temporal trends in annual average agricultural rental prices for England (£/ha), were explored by univariate linear regression models comparing variables of interest to either FAT or FBT Agreement prices measured over the period 2001 to 2012[6] (Table 2-3).

Table 2-3 Trend Analysis Summary - Univariate linear regression of relevant metrics versus either Full Agricultural Tenancies (FAT) Agreements or Farm Business Tenancy (FBT) Agreements as measured in (£/ha)

Name	**Alias**	**Years**	**Geographic Extent**	**FAT**		**FBT**	
				R^2	**R^2 Rank**	**R^2**	**R^2 Rank**
Agricultural Price Index - Inputs (2010 = 100) [7]	API-IN	2001 - 2012	UK	0.87*	4	0.01	9
Agricultural Price Index - Outputs (2010 = 100) [7]	API-OUT	2001 - 2012	UK	0.90*	3	0.00	12
Bank of England Base Rate (%) [8]	BOE	2001 - 2012	UK	0.69*	9	0.05	7
Europe Brent Spot Price FOB ($ Per Barrel) [9]	BRENT	2001 - 2012	Europe	0.79*	6	0.06	6
Consumer Price Index (2005 = 100) [10]	CPI	2001 - 2012	UK	0.96*	1	0.01	9
Retail Prices Index (1987 = 100) [9]	RPI	2001 - 2012	UK	0.91*	2	0.03	8
Workplace Based Gross Value Added (£ billion) [11]	GVA	2001 - 2012	UK	0.75*	7	0.18	4
Index of Labour Costs Per Hour - All (2000 = 100) [12]	ILCH-ALL	2001 - 2012	UK	0.75*	7	0.17	5
Index of Labour Costs Per Hour - AFF (2000 = 100) [12]	ILCH-AFF	2001 - 2012	UK	0.65*	10	0.22	3
Fertiliser - Blended bags (£/t) [13]	FERT	2001 - 2012	UK	0.63*	11	0.01	9

* ANOVA F-test statistically significant at the 95% level of confidence.

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[6] www.gov.uk/government/statistics/farm-rents
[7] www.gov.uk/government/uploads/system/uploads/attachment_data/file/224012/defra-stats-foodfarm-farmgate-api-2000-130124i.xls
[8] www.bankofengland.co.uk/boeapps/iadb/NewInterMed.asp?Travel=NIx
[9] www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=rbrte&f=a
[10] www.ons.gov.uk/ons/rel/cpi/consumer-price-indices/december-2014/consumer-price-inflation-reference-tables.xls
[11] www.ons.gov.uk/ons/rel/regional-accounts/regional-gross-value-added--income-approach-/december-2014/rft-nuts1.xls
[12] www.ons.gov.uk/ons/rel/ilch/index-of-labour-costs-per-hour--experimental-/q4-2014/stb-ilch-q4-2014.html
[13] http://dairy.ahdb.org.uk/non_umbraco/download.aspx?media=5146

The strength of relationship between rental agreement prices and other variables was evaluated with the R-squared statistic, which measures how well the fitted regression line explains the variation. R-squared is expressed as a number between 0 and 1, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the fitted regression line.

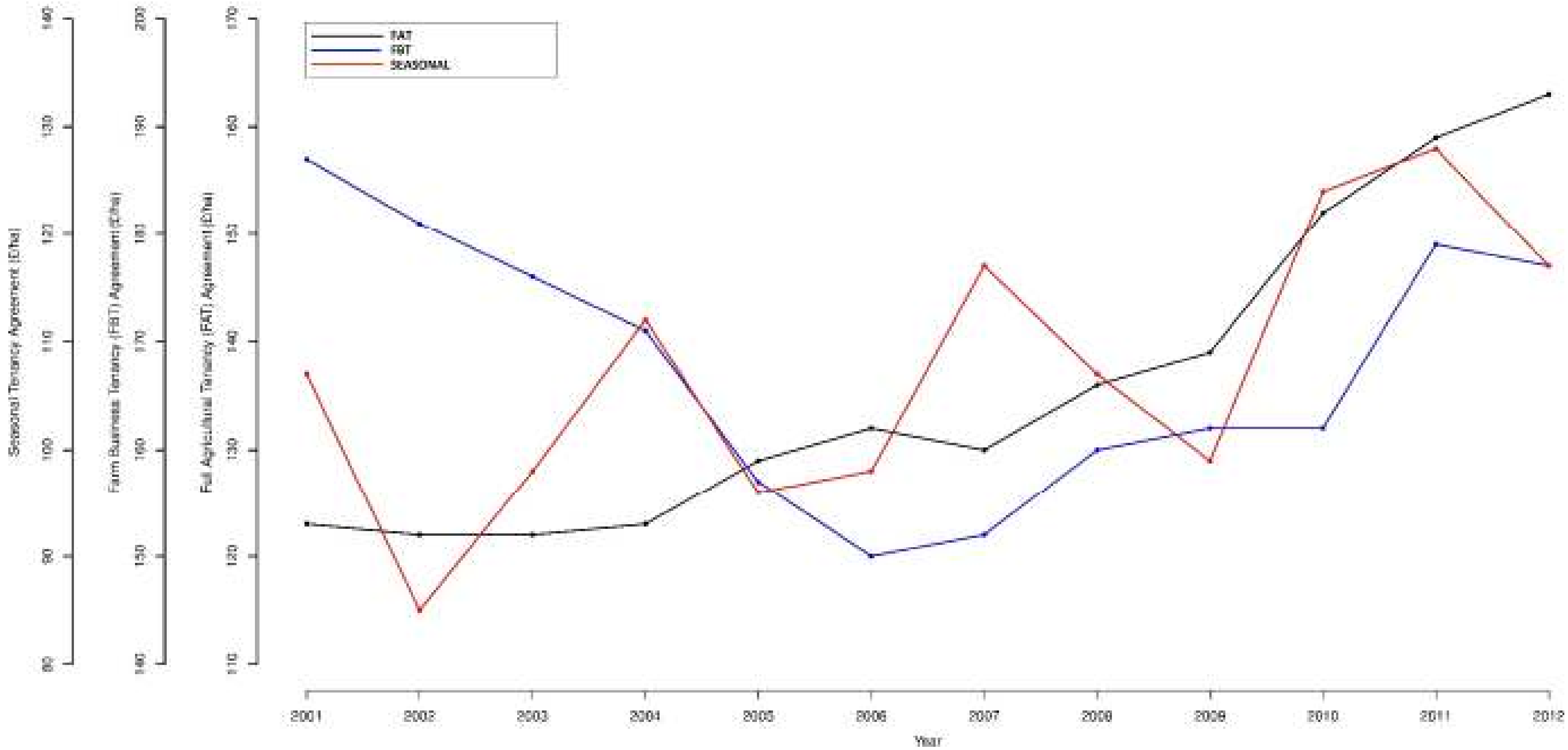


Figure 2-3 Trend Analysis Plot - Full Agricultural Tenancies (FAT) Farm Business Tenancy (FBT) and Seasonal Agreement estimates of annual average rental rates in England

UK measures of inflation, in the form of the CPI (Consumer Price Index) and RPI (Retail Price Index), are shown to have the greatest influence on FAT rental agreement rates in England (R^2 >0.9). The RPI and CPI measure changes in the price of a basket of consumer goods and services purchased by households, with the CPI excluding household running costs (i.e. rises in mortgage payments, rent, council tax, etc.). The correlation matrix of influential variables (predictors) and rental prices (response) reveals these inflation indices to be most strongly related to Agricultural Price Index (Inputs/Outputs) and the Europe Brent Spot Price for oil (Table 2-4).

Table 2-4 Trend Analysis Summary (R-Squared correlation matrix of univariate linear regression model outputs)

	FBS FAT	FBS FBT	API-IN	API -OUT	BOE	BRENT	CPI	RPI	GVA	ILCH-ALL	ILCH-AFF	FERT
FBS FAT	1.00											
FBS FBT	0.00*	1.00										
API-IN	0.87*	0.01	1.00									
API-OUT	0.90*	0.00	0.98*	1.00								
BOE	0.69*	0.05	0.53*	0.61*	1.00							
BRENT	0.79*	0.06	0.91*	0.84*	0.30	1.00						
CPI	0.96*	0.01	0.95*	0.95*	0.66*	0.86*	1.00					
RPI	0.91*	0.03	0.96*	0.93*	0.55*	0.92*	0.98*	1.00				
GVA	0.75*	0.18	0.87*	0.79*	0.40*	0.90*	0.87*	0.94*	1.00			
ILCH-ALL	0.75*	0.17	0.88*	0.80*	0.44*	0.87*	0.87*	0.93*	0.99*	1.00		
ILCH-AFF	0.65*	0.22	0.78*	0.69*	0.44*	0.72*	0.76*	0.80*	0.89*	0.93*	1.00	
FERT	0.63*	0.01	0.90*	0.84*	0.36*	0.79*	0.73*	0.76*	0.71*	0.74*	0.71*	1.00

Measurements recorded only over a partial (2001-09) rather than the full time-series (2001-12)

* ANOVA F-test statistically significant at the 95% level of confidence.
GREEN CELLS: Identify the metrics with the strongest association to either FAT or FBT.
YELLOW CELLS: Indicate where strong linear-correlation exists between a pair of influential metrics, as measured by an R^2 value >0.9.

The following graphs (Figure 2-4, Figure 2-5) show the trends of price per hectare for FAT rental agreements in England compared with both CPI and RPI measures of inflation in the UK.

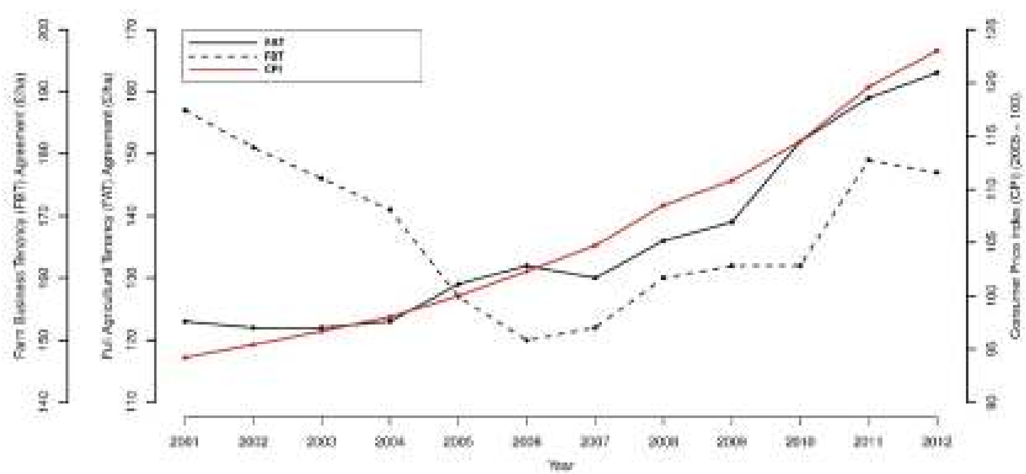


Figure 2-4 Trend Analysis Plot: Full Agricultural Tenancies (FAT) Agreements, Farm Business Tenancy (FBT) Agreements, Consumer Price Index (CPI)

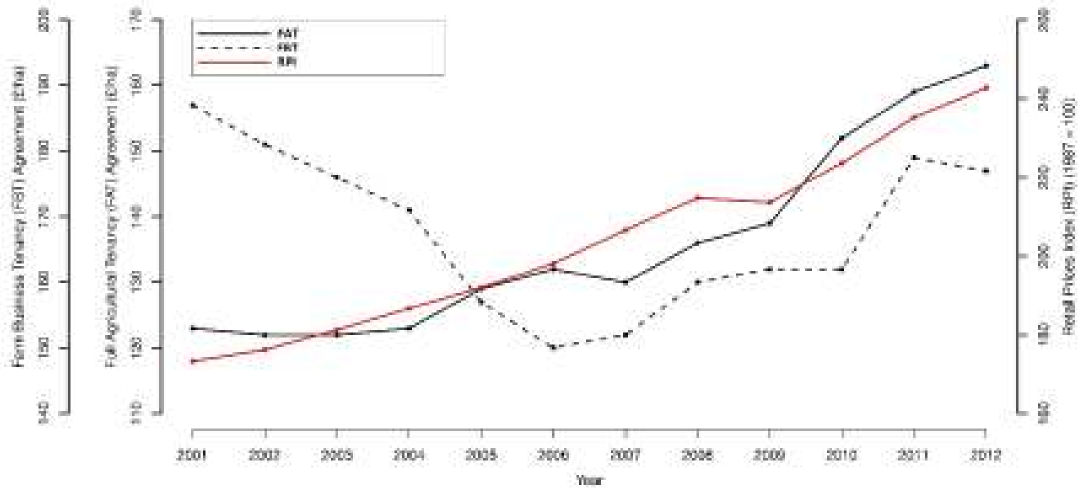


Figure 2-5 Trend Analysis Plot: Full Agricultural Tenancies (FAT) Agreements, Farm Business Tenancy (FBT) Agreements, Retail Prices Index (RPI)

The CPI and the RPI have the largest significant relationship to the farm rents under FAT (R-squared values of 0.96 and 0.91 respectively), but not under FBT.

The ANOVA F-Statistic is shown to have a p-value <0.05 indicating overall model validity (Table 2-5). The CPI variable is also shown to have a p-value <0.05, suggesting that the relationship between CPI and farm rental prices under FAT is statistically significant at the 95% confidence level. While incremental tenancy price increases in relation to CPI can be predicted, the baseline (intercept) has some uncertainty (p-value > 0.05), resulting in a limited back-trajectory performance to the 90th percent confidence level of statistical significance.

The ANOVA F-Statistic is shown to have a p-value <0.05 indicating overall model validity (Table 2-6). The RPI variable is also shown to have a p-value <0.05, suggesting that the relationship between RPI and farm rental prices under FAT is statistically significant at the 95% confidence level. While incremental tenancy price increases in relation to RPI can be predicted, the baseline (intercept) is uncertain (p-value > 0.05), resulting in a poor back-trajectory performance.

Table 2-5 FAT Vs CPI (2005 = 100)

R-Squared: 0.96
Residual Standard Error: 3.143 on 10 Degrees of Freedom
F-statistic: 228.3 on 1 and 10 Degrees of Freedom (P-Value <0.001)

	Estimate	**Std. Error**	**T-Value**	**P-Value**
Intercept	-20.669	10.398	-1.988	0.075
CPI (2005 = 100)	1.481	0.098	15.109	< 0.001

Table 2-6 FAT Vs RPI (1987 = 100)

R-Squared: 0.91
Residual Standard Error: 4.482 on 10 Degrees of Freedom
F-statistic: 107.2 on 1 and 10 Degrees of Freedom (P-Value <0.001)

	Estimate	**Std. Error**	**T-Value**	**P-Value**
Intercept	11.531	12.077	0.955	0.362
RPI (1987 = 100)	0.610	0.059	10.352	< 0.001

2.3.1 Summary

Strong linear associations were observed between UK measures of inflation, in the form of the Consumer Price Index (CPI), Retail Prices Index (RPI) and annual average Full Agricultural Tenancies (FAT) Agreements in England (R-squared > 0.9). The ANOVA F-Statistic revealed the univariate linear regression models for these variables to be valid, as did the t-test of their regression parameter coefficient (p-value <0.05). While incremental FAT price increases in relation to CPI can be predicted, the baselines were shown to be uncertain (p-value > 0.05), limiting their use to prediction of the rate of change, rather than prediction of absolute change.

A different trend was observed for Farm Business Tenancy (FBT) agreements, which have not experienced a consistent price increase as observed for FAT agreements. Rather, FBT agreements gradually declined from 2001 to 2006, before rising at a similar rate to FAT agreements. Very few markers of interest were found to be of relevance in modelling this trend, with the exception of the size of holdings in England (p-value > 0.05). However, caution should be taken when interpreting this relationship as information on holding size was not fully available for the period 2001 to 2009.

It is recommended that the FBS spatial analysis should be repeated with later rental price data when available.

2.4 Testing the hypothesis that bioenergy cropping for anaerobic digestion (AD) is impacting land rental prices in England & Wales

The government has an ambition to increase energy from waste through anaerobic digestion (AD) at all scales. AD can avoid the greenhouse gas emissions from sending waste to landfill and improve nutrient management on farms. As well as renewable energy, AD produces digestate, a material that can, to some extent, replace inorganic fertilisers and avoid the greenhouse gas emissions associated with their production.

There are, however, concerns about the further development of AD plants, with a further shift from food to bioenergy cropping, where the latter demands a higher commodity and land rental values. The development of AD plants is therefore of interest to the debate about the security of food and energy supplies.

Spatial regression approaches were employed to model the relationship between agricultural land rental prices and several proxies associated with the production-conversion process of energy crops in England and Wales; after adjusting for the influence of general confounding factors. Confounding factors are background variables that are not of direct interested, but if unaccounted for, can lead to bias that distorts the magnitude of the relationship between rental prices and the factors of interest.

Table 2-7 provides a list of parameters modelled against the logarithmic-10 (LOG_{10}) transformed "Total Agricultural Land Rental Rate" (£/ha) for 2012[14], recorded in Ordnance Survey Great Britain (OSGB) 10 km^2 lattice grids. Appendix 1 presents an in-depth description of the underlying data, the spatial modelling processes, and evaluation of the final outputs.

[14] A transformation of the dependent variable was conducted to create a model input and output (regression residuals) dataset with a normal distribution. This is fundamental of regression modelling to uphold the reliability of model diagnostic procedures, with non-normality of the error terms impacting the precision of coefficient significance.

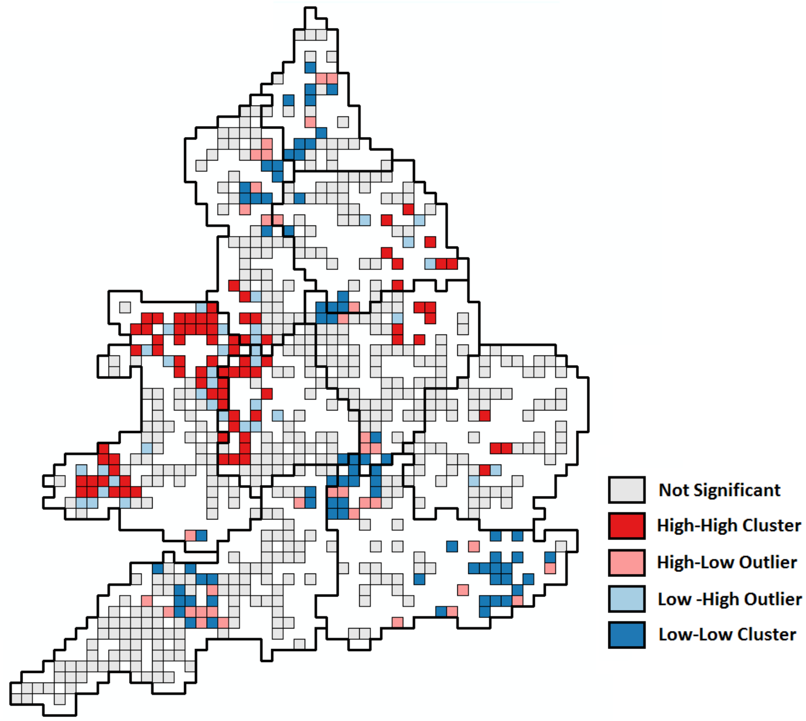
Table 2-7 Agro-economic variables used to predict agricultural land rental prices across 682 OSGB 10 km² gridded data cells

Reference	**Description**	**Year**	**Model Influence**
Defra (2015a), WG (2015a)	(X1) Land occupied by Full Agricultural Tenancy (FAT) Agreements (%)	2012	Confounding
Natural England (2010), MAFF (1988)	(X2) Agricultural Land Classification (ALC)	1988/2010	
OS (2015)	(X3) LOG_{10} "Proximity to the motorway network" (km)	2014	
ONS (2011a)	(X4) LOG_{10} "Proximity to urban area + 1" (km)	2011	
ONS (2011b)	(X5) Carstair's Index of Deprivation (z-score)	2011	
Defra (2015b), WG (2015b)	(X6) Maize Coverage (ha)	2013	Fodder demand
LandIS (2014)	(X7) Agricultural Land Suited for Maize (%)	2014	Land at risk
WRAP (2014)	(X8) LOG_{10} "Proximity to Anaerobic Digestion (AD) Plant" (km)	2012	Bioenergy demand
WRAP (2014)	(X9) Nearest AD Plant Output (kWe)	2012	Bioenergy demand: Interaction
WRAP (2014)	(X10) Influence of "Crop" Fed AD Plants (%)	2012	

An exploratory spatial data analysis of the "LOG_{10} Total Agricultural Land Rental Rate" (£/ha), using the Local Moran's I statistic (Anselin, 1995), identified a significant yet mild pattern of spatial correlation in the data at the national level ($P \leq 0.01$).

The Local Moran's I statistic is used to evaluate the level of similarity (or dissimilarity) between an individual observation in the dataset (i) and those values recorded at neighbouring locations (j). This is achieved through a comparison of z-scores, so that the dataset values are nationally normalised. Clustering occurs when a location reports similar values to its neighbours. A cluster with values higher than the nationally expected value is classed as a hot-spot, whereas a cluster with relatively low values is called a cold-spot. Outliers are where the value at a given location is the polar opposite to the trend recorded at neighbouring locations.

A visual inspection of the Local Moran's I statistic's underlying spatial elements shows that a prominent hot-spot in LOG_{10} rental prices (LOG_{10} [£/ha]) occurs along the Welsh border, extending from Hereford up to Telford and Shrewsbury (2.2 to 2.5), around Snowdonia National Park (2.2 to 2.6) and thirdly along Pembrokeshire coastline (2.3 to 2.8). Smaller hot-spot structures are found encircling Lincoln (2.3), and to the north around Hull and York (2.2 to 2.6). Cold-spots, representative of areas with relatively low agricultural rental prices, are found around the south-eastern towns of Maidstone and Tunbridge Wells (1.8 to 2.0), throughout the South Midlands (1.8 to 2.0), and across a north-easterly stretch of land bounded by the Lake District and the Yorkshire Dales (1.7 to 2.1).



Category	Autocorrelation	Z-Score Interpretation
High-High (H:H)	Positive	A high value feature neighboured by equally high value features
High-Low (H:L)	Negative	A high value feature (outlier) neighboured by low value features
Low-Low (L:L)	Positive	A low value feature neighboured by equally low value features
Low-High (L:H)	Negative	A low value feature (outlier) neighboured by high value features

Figure 2-6 Local Moran's I output for rates of agricultural land rental (£/ha) in 2012, under a row-standardised fixed distance band weighting scheme of 50 km (P≤0.05)

2.4.1 Regression Analysis

The three regression based modelling approaches used to test the influence of AD plants on land rental prices in England and Wales are outlined below. These are ordered in relation to the increased emphasis placed on accounting for the effect of spatial influence on rental values.

Ordinary Least Squares (OLS) regression is the standard approach used to describe how variation in an explanatory variable (i.e. land quality, proximity to AD plant, etc.) produces a change on the dependent variable, which in this analysis was agricultural land rental price. For this particular model, a single fixed response gradient was assigned to each individual explanatory variable representative of the national 'average' rate of change. However, the assumption of a spatially uniform modelled relationship would be quite misleading if such relationships are spatially intrinsically different.

The use of the Spatial Error Model (SEM) is a conceptually more appropriate approach for describing the 'average' rate of change, where there is a geographically uneven distribution in the values of the modelled variables. Here, spatial dependency is calculated and removed before the explanatory and dependent variables are regressed under an OLS approach; this corrects for any geographical bias in the model estimates. The description of 'average' rates of change is of particular relevance when seeking to inform policy at a national level.

Unlike the OLS and SEM strategies, Geographically Weighted Regression (GWR) fully embraces the possibility of geographically unique responses to a given influence by constructing spatially weighted OLS models at each individual observation in the dataset. The creation of coefficients unique to each location (spatially varying) enables the richness of the underlying data to be explored, thereby identifying highly-localised relations which may have been smoothed away by the aforementioned national modelling strategies.

2.4.2 Ordinary Least Squares (OLS)

A traditional regression approach was initially used to examine the effects of nine explanatory agro-economic variables on agricultural land rental prices in 2012. While representing a relatively poor goodness-of-fit between the explanatory and dependent variable, overall model performance tests indicated that an acceptable list of explanatory variables had been modelled.

Significant spatial clustering amongst OLS model residuals, in conjunction with the knowledge of localised rent patterns (Figure 2-6), reinforce the need for modelling approaches to account for the dataset's spatial nature.

2.4.3 Spatial Error Model (SEM)

A type of spatial regression known as the Spatial Error Model (SEM), was used to determine rates of change in rent, representative of the average national level of influence from each of the agro-economic variables. In SEMs, spatial dependence enters through the errors (nuisance) rather than through the systematic component (substance) as seen in traditional regression approaches; thus correcting for the potentially biasing influence of spatial autocorrelation acting on processes known a-priori, listed in Figure 2-6.

A SEM considering data observations to be spatially related when separated by a distance of less than 80 km, was found to provide optimised fixed parameter estimates for the agro-economic variables of interest. On average, each OSGB 10 km^2 observation cell was evenly influenced (row-standardised) by the 72 nearest neighbouring observations.

Statistically significant underlying trends in the data at the 95% level of confidence were identified under the 80 km spatial continuity scheme Spatial Error Model (SEM):

- An average baseline price of rent across England and Wales of £163.49 (95% CI: 138.47 to 193.05) per ha.
- Rental prices to increase in line with the quality of agricultural land, with Grade 1 land under the Agricultural Land Classification (ALC) commanding the highest price.
- Land rental prices to increase with the uptake of FAT tenancies, perhaps reflective of the stable income that a long-term agreement can provide.

Figure 2-7 summarises the estimated changes in agriculture rental prices (%) associated with a percentile unit shift in an independent variable away from its median (50th percentile) value; as modelled under the 80 km spatial continuity scheme Spatial Error Model (SEM).

Proximity to, or any of the AD plant interaction effects, were not observed to significantly influence agricultural land rental prices; as defined by the SEM's national average rates of change. Subsequently, 'local' approaches in the form of Geographically Weighted Regression (GWR), considered a spatial relation between the 70 nearest neighbouring observations to construct location specific (spatially varying) coefficients. This allowed for the investigation of localised response signals which may have been smoothed away by preceding modelling strategies defining the typical national response.

	Change in rental price (£/ha) associated with the difference between the Nth percentile and the median value of an independent variable (95% confidence interval)			
	1st Percentile	25th Percentile	75th Percentile	99th Percentile
(X1) Land Covered by FAT Agreements (%)	--	--	-2.70	-19.63
(X2) Agricultural Land Classification (ALC)	60.60	6.31	-14.62	-42.49
(X7) Agricultural Land Suited for Maize (%)	-3.95	-3.95	10.66	18.84

Green Cells = Significant at the 0.05 level, White Cells = Correlation significant at the 0.10 level

Figure 2-7 The estimated change (£/ha) in rental price on agricultural land valued at £163.49 per ha associated with a percentile unit shift on an independent variable away from its median (50th percentile) value, as modelled under the 80 km spatial continuity scheme Spatial Error Model (SEM).

2.4.4 Geographically Weighted Regression (GWR)

Table 2-8 provides a regional summary of the geometric change (%) in rent from agro-economic influence where local coefficients from the GWR model were reported at the 5% significance level. To summarise, these values correspond to self-contained changes on the rental baseline as defined by the local intercept value (i.e. a theoretical situation where no other influences on land rental prices are assumed to exist, so the interactions between dependent variables are not considered).

Table 2-8 confirms the presence of spatial non-stationarity, whereby the direction and/or magnitude of a given influence differs across the nation. Under a local modelling approach, the influence of AD plants as indicated by proximity, was associated with raised rental prices in multiple OSGB 10 km^2 cells across Wales (+34.2%), the East of England (+14.8%), and the North West (+13.7%). In contrast, land in the East Midlands (-65.7%) and the South East (-14.5%) was associated with a decrease in rental prices with the influence of AD plants as indicated by proximity.

Mapped GWR outputs demonstrated that the interaction between nearest AD plant and a given OSGB 10 km^2 grid cell in terms of output, feed type, and proximity, significantly influences land rental prices within three unique locations at the 5% significance level:

- A cluster of seven cells extending from the Oxfordshire market town of Banbury to Milton Keynes, was associated with a 5.7 to 44.7% (95% CI: 0.1 to 101.0) geometric increase in rent from a medium mixed-fed AD plant (499 kWe).
- A cluster of three cells (not disclosed) was associated with a 52.6 to 260.1% (95% CI: -0.05 to 1078.1) geometric increase in rent. It would appear that even though AD plants are impacting rental values at these locations, such grids are unable to effectively respond to this demand, with the agricultural land deemed unsuitable for growing maize.
- A cluster of four cells (not disclosed) was associated with a geometric decrease of -11.7 to -2.3% (95% CI: -20.0 to 0.0) in rent. It would appear that this site sources its feed locally (as indicated by the significance of AD plant proximity), but as it is not restricted to a certain feed type and has only a moderate output (500 kWe) there is not a strong demand for energy crops.

However, when correcting the GWR modelled outputs with the extremely conservative Benjamini-Hochberg (B-H) False Discovery Rate test, no relations were observed to be of significance between land rental prices and the influence of AD plants. Caution must therefore be taken when interpreting these outputs, with such trends requiring confirmation from local case studies.

2.4.5 Summary

Spatial modelling approaches applied to explore the national average response in agricultural land rental prices to several agro-economic variables of interest, detected no significant influence from proximity to, or any of the AD plant interaction effects. Subsequent 'local' approaches in the form of Geographically Weighted Regression (GWR), sought to investigate localised response signals potentially smoothed away when describing rental information at the national level. Under a local modelling approach, the influence of Anaerobic Digestion (AD) plants as indicated by proximity, was associated with raised rental prices in locations across Wales, the East of England, and the North West. Land in the East Midlands and the South East were associated with a decrease in rental prices from the influence of Anaerobic Digestion (AD) plants as indicated by proximity. However, significance between land rental prices and the influence of AD plants was not identified upon correcting the GWR outputs with the extremely conservative Benjamini-Hochberg (B-H) False Discovery Rate. Caution must therefore be taken when interpreting these outputs, with such trends requiring confirmation from local case studies.

In conclusion, AD plants are not found to significantly influence rental prices in a uniform manner across England and Wales. There are high localised areas which may be impacted by the operation of AD plants, but these cannot be confirmed with a true sense of confidence.

Table 2-8 GWR modelled regional 'Average (OSGB 10 km^2 Count)' influence on land rental rates from an individual agro-economic variable (P ≤0.05), if all other independent variables were to have zero influence.

	East Midlands	**East of England**	**North East**	**North West**	**South East**	**South West**	**Wales**	**West Midlands**	**Yorkshire and Humber**
Intercept (£/ha)	146.2 (80)	107.3 (57)	257.5 (33)	190.4 (69)	95.4 (62)	120.9 (87)	168.3 (78)	142.8 (56)	225.3 (57)
(X1) Land Covered by FAT Agreements (%)	--	--	9.5 (9)	6.5 (3)	2.1 (6)	1.5 (45)	-29.7 (1)	--	--
(X2) Agricultural Land Classification (ALC) [P]	-9.0 (24)	66.4 (10)	--	3.0 (6)	12.9 (7)	18.2 (3)	--	-5.0 (14)	3.0 (23)
(X3) LOG_{10} "Motorway Proximity" (km) [P]	--	54.4 (12)	--	36.8 (3)	--	-9.3 (10)	-28.2 (10)	--	--
(X4) LOG_{10} "Urban Proximity + 1" (km) [P]	--	-3.7 (9)	--	--	25.1 (28)	7.3 (10)	28.3 (9)	11.9 (12)	3.0 (8)
(X5) Carstair's Deprivation Index (z-score) [P]	-19.7 (1)	16.3 (12)	--	--	6.5 (10)	--	--	--	-1.9 (2)
(X6) Maize Coverage (ha) [P]	-6.1 (20)	13.7 (12)	--	15.1 (1)	2.9 (6)	14.7 (48)	28.0 (11)	--	-15.3 (8)
(X7) Agricultural Land Suited for Maize (%)	--	--	-51.3 (19)	48.4 (1)	13.0 (3)	--	-36.5 (7)	--	22.5 (1)
(X8) LOG_{10} "AD Plant Proximity" (km) [P]	-65.7 (3)	14.8 (10)	--	13.7 (20)	-14.5 (6)	-45.7 (1)	34.2 (4)	-13.0 (1)	30.0 (1)
(X8-INT A) Nearest AD Plant Output (kWe)	26.0 (12)	37.7 (8)	--	-46.4 (8)	-25.4 (8)	-42.1 (7)	266.8 (13)	-20.4 (2)	-1.7 (4)
(X8-INT B) Influence of "Crop" Fed AD [P]	30.4 (8)	-95.9 (1)	--	10.2 (17)	4.8 (20)	19.3 (2)	25.6 (16)	9.5 (3)	19.5 (1)
(X8 * X8A) [P]	26.3 (9)	21.7 (5)	--	25.9 (2)	26.2 (5)	19.8 (1)	-37.2 (1)	-0.3 (1)	-11.8 (11)
(X8 * X8B) [P]	10.6 (5)	408.6 (8)	--	336.9 (3)	15.9 (5)	--	--	--	-19.9 (2)
(X8A * X8B) [P]	2.8 (8)	1915.7 (1)	--	29.7 (3)	11.6 (4)	--	-69.4 (11)	-10.5 (10)	54.4 (3)
(X8 * X8A * X8B) [P]	25.8 (3)	224.9 (11)	--	1165.9 (3)	17.1 (6)	--	56.7 (1)	-8.0 (2)	-17.7 (8)
Residuals [P]	6.5 (80)	7.7 (62)	3.4 (33)	5.5 (69)	3.9 (62)	2.5 (87)	6.6 (86)	4.0 (57)	7.8 (57)

[P] = Percent change in rent (£/ha) for a the recorded magnitude of a singularly held variable of interest

3 Quantifying the environmental footprint of maize production

In England, the maize growing area has increased from *c.*1,000 ha in the early 1970's to around 170,000 ha in 2014 (Defra, 2014a). Maize is grown for livestock feed and increasingly as a feedstock for anaerobic digestion biogas production but regardless of end use, careful soil management is often needed to reduce the risks of surface runoff as well as sediment and nitrate leaching losses to water in maize cropping systems. Maize is usually established in late spring once soil temperatures have reached 8°C at 10cm depth and is typically harvested between late September and mid-November, when soils can be 'wet', increasing the risks of soil compaction by harvest machinery and the potential for surface runoff and sediment loss to surface water systems. Also bare ground overwinter increases the risks of nitrate leaching losses.

The environmental impact of maize production is receiving increasing public attention, particularly following the flooding in the South-West of England over-winter 2012/2013 (http://www.theguardian.com/commentisfree/2014/feb/17/farmers-uk-flood-maize-soil-protection). More recently, with the updated cross compliance rules farmers now have to comply with new minimum standards of soil management.

The objectives of this analysis were to:

1. Synthesise the available data to assess the environmental impacts of maize production in England and Wales on soil quality, diffuse (water) pollution and biodiversity. Ammonia (NH_3) emissions following the application of digestate to land will also be presented.
2. Examine the potential environmental impacts (costs) and benefits of maize production for use as i) a feedstock for bioenergy production and ii) livestock feed.
3. Using June Agricultural Survey data, assess which agricultural production types are displaced by maize production for use in anaerobic digestion.

3.1 Direct environmental impacts of maize production

3.1.1 Methodology

Results from recent research carried out in the UK, investigating the environmental impacts of maize production were collected using the web-based database "Web of Science" to identify relevant published papers. Key words included maize, sediment, nitrate leaching and erosion. Additional research was also collated on the baseline environmental impacts and mitigation strategies from agro-climatic zone relevant to maize cropping by refining search results for authors' country of affiliation; this included: e.g. Belgium, Denmark, England, France, Germany, Ireland, The Netherlands, New Zealand, Scotland, Switzerland and Wales. In addition, Defra funded projects researching the environmental impacts of maize production were identified using the Defra online database and information from other industry sources e.g. Maize Growers Association (MGA) were assessed.

We have identified 5 key studies that investigated the environmental impacts of maize production in England (Table 3-1). The experimental sites used in these studies largely reflect the main soil and agro-climatic maize growing regions in England. Studies have investigated impacts of maize growing on diffuse water pollution, soil quality and biodiversity.

Table 3-1 Key studies investigating the environmental impact of maize cropping in England

Study	Location	Soil type	Slope	Data collected
Defra study SP0404 *	Devon and Somerset	Light or medium	3% or 8%	Yield, surface runoff, sediment losses, phosphorus (P) losses,
Defra study WQ0140*	Norfolk and Devon	Light or medium	3% or 13%	Yield, surface runoff, sediment losses, P-losses, nitrate leaching, soil quality, direct nitrous oxide emissions, biodiversity (invertebrate & botanical)
Defra study AR0412	Norfolk, Suffolk, Somerset	Light to medium	No data	Yield, biodiversity (invertebrate & botanical)
Palmer and Smith (2013)	South-West England	Light to heavy	No data	Soil structural assessments
Withers and Bailey (2003)	South-West England	Medium	12-14%	Surface runoff and sediment losses

*Also published as Environment Agency report P2-123/1 (Clements and Donaldson, 2002)

3.1.2 Environmental impacts of conventional maize production

Soil Structural quality

Soil structural damage (e.g. compaction and capping) can reduce the vertical movement of water, due to a reduction in total soil porosity. The reduced water infiltration increases the risk of lateral flow of water, either above the layer of compaction (i.e. within the upper surface horizon) or across the soil surface, thereby increasing the risk of surface runoff and associated flooding (Palmer & Smith, 2013).

Palmer & Smith (2013) reported the findings from a soil structural survey carried out in The South West of England, between 2002 & 2011, using visual assessment methods. The soil structural assessments place soils into one of four soil degradation classes (extent of structural degradation: *severe >high >moderate >low*). In total >3000 structural assessments were conducted across a range of soil types and land-uses. Soils with the most structural damage were found on land used to grow late harvested crops, such as maize and potatoes, with *c.*75% of sites showing *high* or *severe* soil structural degradation. Furthermore, one in five of these sites had signs of overland flow (e.g. gully erosion). In comparison, *c.*60% of land used to grow winter cereals showed *high* or *severe* levels of soil structural degradation (Figure 3-1). For permanent grassland and grass ley sites <10% and c.40%, respectively were classed as having high or severe structural degradation.

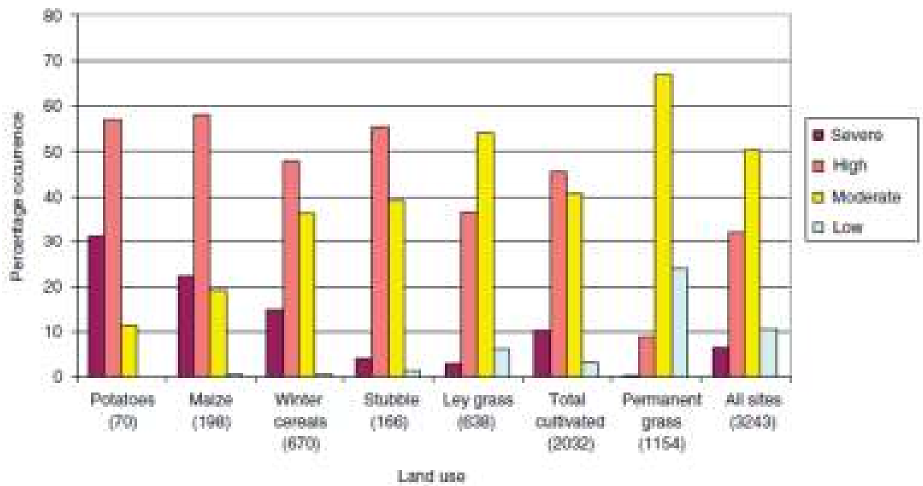


Figure 3-1 Degree of soil degradation under maize and other crops in the South West of England (taken from Palmer & Smith 2013)

In project WQ0140, visual soil structure assessments using 'The Visual Structure Score' method (Peerlkamp, 1967) was carried out on maize crops at two sites (Norfolk and Devon), on soils (at 0-20cm depth) which, had been cultivated using conventional (plough-based) methods, in spring 2013, autumn 2013 and spring 2014. The highest score (10) is given to the least compact and most porous condition, and the lowest score (1) to a massive condition with no structure and few or no cracks. Overall, the conventional plough-based cultivated soil had a good soil structure, scoring a mean ST score of 8 or 9 (Figure 3-2).

Figure 3-2 Examples of visual soil structure (ST) scores taken in spring 2013 at Norfolk (Defra project WQ0140) from conventional (plough-based) cultivation. The highest score (10) is given to the least compact and most porous condition, and the lowest score (1) to a massive condition with no structure and few or no cracks.

Diffuse water pollution

Maize is a spring sown crop, consequently soil is often left bare over winter before crop establishment; increasing the risk of: surface runoff, soil erosion, phosphorus (P) losses and nitrate (NO_3) leaching losses to water, especially on sloping land and in areas with high rainfall. In England, two Defra funded studies, SP0404 and WQ0140, provide the main sources of evidence investigating diffuse water pollution losses from maize cropping (Table 3-2).

Data from WQ0140, have demonstrated that despite low surface runoff volumes, sediment losses on shallow sloping land (*c.*3%) can be high. In 2012-2013, in Norfolk, surface runoff volumes of *c.*2mm, resulted in sediment losses of *c.*1,300 kg ha^{-1}. Conversely, in the same year, in Devon, runoff volumes were much greater at *c.*40 mm, while sediment loses were *c.*900 kg ha^{-1}. Furthermore, sediment losses measured in Norfolk in 2012-2013 were equivalent to those measured in project SP0404 over-winter 1998-1999 (at *c.*1400 kg ha^{-1}). The mean sediment loss from all experiments presented in Table 3-2, was *c.*1 t ha^{-1}. Owens *et al.* (2007) carried out a study in southwest England and measured the amount of sediment captured in Astroturf mats positioned in fields. The greatest amount of sediment deposited occurred on a maize-cropped land (sandy clay loam soil, slope 4^{o}) at 1.15 +/- 1.88 g cm^{-2} this was similar to the amounts recorded from two winter wheat fields at 1.14 +/- 2.26 g cm^{-2} (sandy loam soil, 5^{o} slope) and 1.00 +/- 1.10 g cm^{-2} (sandy clay loam soil, 5^{o} slope).

A number of studies in Europe have measured soil erosion from maize:

- Le Bayon *et al.* (2002) reported that sediment losses from maize over the whole year amounted to *c.*1,400 kg ha^{-1} (soil texture = loam, slope = 2.6°.

- Kwaad *et al.* (1998) in a field experiment carried out in the Netherlands, measured sediment losses of *c.*4000 kg ha^{-1} in a wet winter (1991/1992) (no rainfall data given), while in a dry winter sediment losses were *c*.3480 kg ha^{-1}.

- Van Dijk *et al.* (2005) estimated that mean erosion rate was 36 t ha^{-1} for a catchment dominated by maize cropping (77% of arable land (which itself represents 75% of total catchment)).

- Gabriels *et al.* (2003) used the Universal Soil Loss Equation (USLE) to identify high risk rotations. The rotation with the second highest risk of erosion was: maize/maize/maize/potatoes, however, sowing ryegrass after maize reduced the risk. Other rotations with a low risk of erosion included: sugar beet/winter wheat/ potatoes/ winter wheat and winter wheat/ winter barley/ sugar beet.

- Fiener & Auerswald (2007) compared the differences in erosion from potatoes and maize and how they impacted on soil erosion from a following winter wheat crop. During the vegetative period (May to August) mean monthly sediment losses were *c.*6, *c.*17 & *c.*20 kg ha^{-1} from winter wheat, potatoes and maize, respectively. Over the year sediment losses from potatoes (224 kg ha^{-1} yr^{-1}) were four times greater than from maize (56 kg ha^{-1} yr^{-1}). Soil loss from a potato-winter wheat sequence (*c.*41 kg ha^{-1} mo^{-1}) were two times greater than a maize-winter wheat sequence (*c.*19 kg ha^{-1} mo^{-1}). It was concluded that the greater soil losses in winter wheat following potatoes compared to maize was due to 1) reduced surface cover after harvest (e.g. 45% of the cover remained after maize harvest), 2) disaggregation of larger aggregates during potato harvest, and 3) lower aggregate stability.

The evidence from the literature review demonstrated that, sediment losses measured from maize cropped land are within the range of median annual soil losses reported for other tillage crops on erodible land, which is typically between the range of 0.2 and 5 t ha^{-1} (Boardman 1990; Chambers *et al.,* 1992; Evans 1993, in Chambers and Garwood, 2000). While , over a 4 year period (1990-1994) in England and Wales, Chambers and Garwood (2000) measured mean soil erosion rates of 4 t ha^{-1} yr^{-1} and reported that soil erosion generally occurred on autumn sowed crops, winter cereals, oilseed rape and reseeded grass where vegetation cover was minimal. Some exceptionally high losses have been reported for both maize (36 t ha^{-1}) (Van Dijk *et al.*, 2005), post-harvest potatoes and winter cereal fields of between 24 to 180 m^{3} ha^{-1} (Broadman *et al.*, 2009).

Rickson (2014) reported that erosion rates ranged from 0.1 to *c.*23 t ha^{-1} yr^{-1} for arable land and 0.02 to *c.5* t ha^{-1} yr^{-1} for grassland and pasture. Furthermore, there is evidence that erosion rates are likely to increase in the future due to: 1) an increase in 'erosive' crops (*i.e. potatoes, asparagus, spring sown cereals, winter cereals, forage maize, sugar beet, field vegetables, salad crops and soft fruit*); 2) the conversion of pasture to arable land; 3) increase in livestock intensity; 4) change in sowing from spring to autumn timing; and 5) increasing use of tramlines.

Phosphorus has low solubility and is strongly bound to finer particulates (<2 µm), which in turn are frequently transported in runoff. Furthermore, in surface runoff from bare ground/ low plant cover the majority of soil lost is in particulate form (Pierzynski *et al.* 2000, Silgram 2004).Consistent with this, in both SP0404 & WQ0140, P losses in surface runoff reflected sediment losses. The greatest P losses were recorded in Devon (over-winter 2000, project SP0404) with *c.*3 kg P ha^{-1} lost. Across all studies (presented in Table 3-2) the mean over-winter P-losses from maize stubble was *c.*2 kg P ha^{-1}.

In comparison, Defra-funded projects PE0206 – field testing of mitigation options (Defra, 2008), showed that tramline wheelings were a major transport pathway for surface runoff, sediment, and P losses from winter cereals on moderate slopes. Over-winter losses from ploughed land with tramlines ranged from *c.*1 to *c.*75 mm for surface runoff, <10 to *c.*4800 kg ha^{-1} for suspended sediment and from 0.01 to *c.*3 kg ha^{-1} for total P-losses. In addition, Chambers and Garward (2000) estimated that, mean P losses would equate to 3.4 kg P ha^{-1}, (based on typically topsoil P contents of *c.*860 mg kg^{-1}) when mean soil erosion rates were 4 t ha^{-1} yr^{-1}.

Surface runoff volumes in the experiments presented in Table 3-2 range from <1 mm to *c.*52 mm, these losses are within the range of surface runoff reported from winter cereals on ploughed land with tramlines *c.*1mm to 75mm (Defra, 2008a). This is consistent with studies carried out elsewhere in Europe: Leonard *et al.* (2006), measured runoff from maize, sugar beet and winter wheat fields on low sloping soils; runoff ranged from 0.1 to 4.3 % of rainfall and there were no consistent differences between crops. Kwaad *et al.* (1998) (also reported in Van Dijk *et al.* 1996) measured runoff volumes of *c.*82 mm in a wet winter (1991/1992) (no rainfall data given), while in a dry winter runoff was *c*.22 mm. Laloy & Bielders (2010), measured runoff from maize over-winter of between *c.*57 to *c.*66.mm.

The results demonstrate that the magnitude of surface runoff, sediment and total P losses from maize cropping are comparable with losses measured from fields where over-winter ground cover is minimal, e.g. cereal stubble.

Light textured soils, with no or little over-winter ground cover are susceptible to NO_3-leaching losses. Over-winter NO_3-N leaching losses from maize stubble, have been measured in WQ0140 (Table 2-1Table 3-2). At the Norfolk site (sandy loam soil) NO_3-N leaching losses were *c.*80 kg NO_3-N ha^{-1} and *c.*40 kg NO_3-N ha^{-1} over-winter 2012-2013 and 2013-2014, respectively. In Defra project, NT1825 (MIDaS2) mean annual (1997 – 2000) nitrate leaching losses from maize ranged from 8 to 36 kg NO_3-N ha^{-1} in comparison losses from perennial ryegrass ranged from 10 to 17 kg NO_3-N ha^{-1}. These Nitrate leaching losses were lower than those reported in MIDaS1 in which nitrate leaching losses from maize ranged from 24-79 kg NO_3-N ha^{-1} following higher N-application rates (i.e. up to 250 kg N ha^{-1}). Following autumn application of slurry project NT1851 reported over-winter nitrate leaching losses of *c.*2-3 kg NO_3-N ha^{-1} from grassland (overwinter rainfall = 217 mm) and from maize stubble (in an exceptionally wet winter, rainfall = 350 mm) losses of *c.*60-106 kg NO_3-N ha^{-1}. On the maize experiment it was estimated that approximately 11-14% of the total slurry-N applied was lost as NO_3-N, while Chambers *et al*., (2000) obtained similar losses of slurry-N, averaging 8 %, from November dates of slurry application to grassland at four sites over a four-year period from 1990/91 to 1993/94. Overall project NT1825, concluded that up to 160 kg N ha^{-1} and up to 300 kg N ha^{-1}could be applied to maize and grass, respectively, without exceeding the EC limit of 50 mg l^{-1} yr^{-1} (Defra, 2002b).

Similarly over-winter NO_3-N leaching losses from a field experiment carried out in Germany reported mean nitrate leaching losses of 52-77 kg NO_3-N ha^{-1} (Muller *et al*., 2011) and Svobodo *et al*. (2013) reported NO_3-N leaching losses of 48-67 kg ha^{-1} following the application of N at optimal N input. Broeke *et al.* (1999), in a modelling study reported that average nitrate N concentrations will be higher from grass (3.6 -19.4 mg l^{-1} than maize (3.5 -15.1 mg l^{-1}) because grassland is a more intensive system and N inputs will be greater. Hermann *et al.* (2005) measured NO_3- concentrations in soil solution in 4 out 5 years of typically less than 50 mg l^{-1}. However in one year NO_3- concentrations were closer to 100 mg l^{-1}.

In comparison to other crops, Johnson *et al* (2002) reported mean NO_3-N leaching losses from a calcareous sandy loam soil over a 5 year crop rotation (winter barley, oilseed rape, winter wheat (for feed), peas and winter weed (for milling) of *c.*50 kg N ha^{-1}. Like maize, main crop potatoes are typically harvested after mid-September making it difficult to establish a following crop in the autumn. Shepherd & Lord (1996), measured high NO_3-N leaching losses (mean over 4 years = *c.*70 kg NO_3-N ha^{-1}) after main crop potatoes when left fallow post-harvest. These findings demonstrate that nitrate leaching losses measured from maize are similar to losses from other arable crops.

Wachendoff *et al.* (2006) reported that when mineral nitrogen fertiliser was applied to maize to match optimal N-rates, NO_3 leaching losses were as low as cut grass. While Kayser *et al*. (2011), carried out an experiment on maize in North-West Germany, in which cattle, pig slurry or mineral nitrogen fertiliser was applied at 4-rates (0 to 240 kg N ha^{-1}) and overwinter nitrate leaching losses were measured. Nitrate leaching ranged from 81 to 176 kg N ha^{-1}, this corresponded to large autumn SMN contents of 152-272 kg N ha^{-1}.As is the case for all crops, this suggests that, high NO_3 leaching losses can occur when N is applied in excess of crop requirement.

A number of European studies have investigated the critical N-loads in maize at which the EC nitrate limit (50 mg l^{-1} NO_3 l) is exceeded; Boumans *et al.* (2005) stated that a critical load of 210 kg NO_3-N ha^{-1} was appropriate for either grassland, maize or other arable land. Heumann *et al.* (2013) and Sovobada (2013) reported that NO_3-N leaching increased exponentially when N was applied at high rates (e.g. above 150 kg N ha^{-1}). Furthermore, Heumann *et al.* (2013) reported that the increase NO_3 leaching at higher N-rates was more rapid in maize (6-fold) compared to rye or winter barley which showed a 2-fold increase.

Evidently, as with all crops, it is important that soil nitrogen supply (SNS) is accounted for before applying manufactured fertiliser in order to minimise N-surplus and therefore NO_3 leaching losses (Herrmann, 2005; Verloop *et al.*, 2006, Möller *et al.* 2011 and Heumann, 2013). The importance of accounting for mineralisable nitrogen was highlighted by Heumann *et al.* (2013), who reported that total N-uptake in unfertilised silage maize was 3 times greater (i.e. *c.*87 kg ha^{-1}) than winter barley. This may be due to the later harvest of maize compared to cereals, which allows more time for mineralisable N uptake; a similar relationship has also been reported between sugar beet and cereals (Engels and Kuhlmann, 1993; Heumann *et al*., 2013). Möller *et al.* (2011), reported that whilst it is recommended (by the Bavarian extension service) that farmers apply 180-200 kg N ha-^{1}, one third of farmers over-fertilise the maize crop. In comparison, the UK Nitrate Vulnerable Zone (NVZ) regulations state that the N-max limit for forage maize is 150 kg N ha^{-1}.

Table 3-2 Baseline diffuse water pollution from maize cropping, summary of results from recent field studies carried out in England

Study	Site	Year of measurement	Soil texture	Field slope (%)	Cultivation method	Rainfall[1] (mm)	Runoff (mm)	Total runoff (% of rainfall)	Sediment loss (kg/ha)	NO_3-N leaching loss (kg/ha)	Total P losses (g/ha)
Defra study SP0404	North Wyke	2000	Sandy clay loam	5	nd	199	43.3	22	719	-	3,114
Defra study SP0404	North Wyke	2001	Sandy clay loam	5	nd	340	47.0	14	-	-	-
Defra study SP0404	Long Ashton	1998/1999	Silty clay loam	8	Conventional ploughed	nd	33.7	nd	1,379	-	2,055
Defra study SP0404	Long Ashton	1999/2000	Silty clay loam	8	nd	nd	8.6	nd	33	-	-
Defra study SP0404	Long Ashton	2000/2001	Silty clay loam	8	nd	264	22.3	9	-	-	-
Defra WQ0140 study[2]	Norfolk	2012/2013	sandy loam	3	Conventional ploughed	152	2.3	2	1,331	82	1,460
Defra WQ0140 study[2]	Norfolk	2013/2014	sandy loam	3	Conventional ploughed	238	0.7	<1	335	40	400
Defra WQ0140 study[2]	Devon	2012/2013	sandy silt loam	13	Conventional ploughed	425	41.5	10	910	-	1,320
Defra WQ0140 study[2]	Devon	2013/2014	sandy silt loam	13	Conventional ploughed	590	51.4	9	1,375	-	2,440

Notes:

not measured indicated by '-'; **nd** = no data

[1]total rainfall - during surface runoff measurement period, approximately from end of October to end of March; **[2]**Unpublished results from WQ0140

Biodiversity

Maize has low tolerance to weed competition, especially at early growth stages between the 4-6 leaf stage, when weeds can easily outcompete maize (MGA per. comm.). Herbicide use controls weeds and can reduce the food and habitat resources for higher trophic levels (e.g. bees, farmland birds and insects). Once a maize crop has established, the plants shade the ground hindering weed growth (Finke *et al*., 1999). Firbank *et al.* (2003) reported that compared to oilseed rape and sugar beet, maize had the lowest biodiversity for both flora and fauna. Overall, Defra-funded project AR0124 (Defra, 2001a), reported a good relationship between weed biomass and numbers of some groups of invertebrates including carabid and stapylinid beetles, Diptera, Heteroptera and hymenopterous parasites and with weed seed production. More recently studies have focused on strategies for increasing biodiversity in maize cropping, either by reducing herbicide use or by using ground cover.

Soil organic carbon content

Typically, almost all of the above-ground material (Leaves, stalks and cobs) of a maize crop is removed either to produce silage for livestock feed or as a feedstock for anaerobic digestion, leaving just maize stubble being incorporated into the soil. In a meta-analysis, Anderson-Teixeria (2009) – found that corn residue harvest (at 25-100% removal) reduced topsoil soil organic carbon (SOC) content, losses by 3,000-8,000 kg ha^{-1}, with losses increasing linearly with residue removal.

Kirk *et al*. (2012) used the Roth-C model to simulate changes in SOC following under-sowing maize with a cover crop. It was found that within one year, under-sowing maize had no effect on SOC contents. Other studies have shown that there is some evidence to suggest that soil under maize can have a slightly greater carbon (C) content (1.30 and 0.68%) than soil under wheat (1.20 and 0.45%) at 0-30 and 30-45 cm depths respectively, presumably due to different rooting characteristics (Helfrich *et al*., 2007; Kirk *et al.,* 2012). While Möller *et al.* (2011) estimated that soil humus budgets under maize will decrease by *c.*10% from 132 to 120 kg humus C ha^{-1} year^{-1}.

When assessing the impact of maize in comparison to other crops on SOC contents it is important to consider both the above and below ground residue returned. Given that almost all of the above ground residue from maize crops is removed it likely that impacts on SOC contents will be comparable to straw removal. Powlson *et al.* (2011) cautioned against the removal of straw, which in the long-term could lead to a reduction in SOC content and a deterioration in soil physical properties. In a recent review of the impacts of straw removal, Nicholson *et al.* (2014) stated that there is a clear trend for SOC content to be increased by straw incorporation (and depleted by straw removal) although by small amounts. Furthermore, Nicholson *et al* (2014) estimated that using current average GB straw yields (3.4 t/ha) the amount of C returned to the topsoil is likely to be *c.*150 kg/ha/yr for winter wheat and *c.*80 kg/ha/yr for oilseed rape straw, this equates to 0.16% and 0.09% of topsoil C. In comparison, typical application rates (at rates equivalent to 250 kgN/ha) of farmyard manure, biosolids and green compost increase topsoil OC contents by 630, 1500, 1400 kg/ha/yr (Nicholson *et al*., 2014; Powlson *et al*., 2012).

Risk of spreading Fusarium from maize-based digestate.

Mycotoxins are toxic chemicals produced by specific fungi which infect crops either in the field by Fusarium species or during storage by Penicillium species. *Fusarium* can have potential negative effects on the quality and yields of cereal crops. The most common Fusarium mycotoxins of concern are deoxynivalenol (DON) and zearalenone (ZON), and there are legal limits for both of these toxins in wheat intended for human consumption (1250 µg/kg DON & 100 µg/kg ZON; EC/1881/2006) and guidance limits for feed grain (8000 µg/kg DON & 2000 µg/kg ZON; EC/576/2006).

As part of WRAP project (OAV036-008) the risks associated with spreading digestate from maize-based feedstock which may contain significant populations of *Fusarium* spp was assessed. The risks associated with batch pasteurisation and continuous mesophilic anaerobic digestion were compared.

Overall the study concluded that because *Fusarium* cannot survive during batch pasteurisation (where the feedstock is heated to 70^{o} C for 1 hour) the use of pasteurised maize-based digestate on land destined for maize production should not present a risk of crop mycotoxin contamination. The mesophilic anaerobic digestion process (MAD) was shown to reduce initial Fusarium levels, however viable spores were still present in the digestate at the end of the digestion process. The study concluded application of unpasteurised maize-based digestate on land used for wheat production presented a risk of mycotoxin contamination and guidance from the HGCA (see http://cereals.ahdb.org.uk/) suggests that rotations where wheat follows maize should be considered high risk for mycotoxin production.

Ploughing maize based digestate into the soil is likely to reduce the risks of mycotoxin production by ensuring that Fusarium spore production does not take place on organic matter or on the soil surface (HGCA, 2007).

Ammonia emissions following application of digestate

The anaerobic digestion process converts organic forms of N into readily available nitrogen (RAN), producing a material that is high in RAN (e.g. *c.*80% of total N (WRAP project *DC-Agri*)), some of which will be lost by ammonia (NH_3) volatilisation during storage and application.

As part of Defra project WQ0140 NH_3 losses were measured at two field sites following applications of crop-based digestate, manure-based digestate, separated fibre from crop-based digestate and cattle slurry applications to maize. Overall, it was found that ammonia losses were greater following the application of crop-based digestate (mean losses *c.*30- 50% of N applied) than following cattle slurry (*c.*15 -20% of N applied) which may reflect the higher pH of the crop based digestate. This is consistent with the results from the *DC-Agri* project which concluded that the ammonia emissions from the food-based digestates (*c.*40% of total N applied) compared to livestock slurry (*c.*30% of total N applied); was partly due to the greater ammonium content of the food-based digestate and partly to its elevated pH (mean 8.3). In comparison, project NT1851 (Defra, 2001b) reported that NH_3-N losses from cattle slurry applied (in the autumn or spring) to maize ranged from *c.*2-4 % of total N-applied.

The nutrient content of digestate is directly related to the feedstock used (WRAP, 2012). Furthermore, when digestate is separated the nutrient content of the solid and liquid fractions will vary depending on the methods used. For example, in project WQ0140, a crop-based fibre digestate which was separated using a belt and centrifugal supplied, *c.*120 kg NH_4-N ha^{-1}, (exceeding the amount supplied by either cattle slurry or manure-based digestate). While the fibre fraction separated using conventional farm slurry separation equipment, supplied, <10 kg NH_4-N ha^{-1}.

The nutrients supplied by digestate will displace the need for manufactured fertiliser (N, P, K and S) applications to meet optimal crop nutrient requirements and consequently the environmental impacts associated with manufactured fertiliser production (e.g. energy use, the use of fossil fuels and finite raw materials such as rock phosphate) will be reduced. A nutrient management plan and access to nutrient management guidance and software tools (e.g. MANNER-NPK) can help farmers maximise the nutrient use efficiency of digestate applications and minimise the risks of nitrogen and phosphorus losses to the environment. The amount of crop available nitrogen supplied by digestate applications will vary depending with for example application method, timing and soil type. To maximise crop available N farmers are advised to apply digestate in the spring to the growing crop; the use of precision spreading equipment instead of surface broadcast applications is likely to reduce NH_3 emissions.

Summary of potential environmental impacts from conventional maize production

Soil surveys have shown that late harvested crops, such as maize and potatoes, show more signs of soil degradation due to trafficking during harvest operations, etc. when soils are wet. The evidence reviewed indicates that:

- Surface runoff from conventional maize cropping is <1 mm to *c.*80 mm. These losses are similar to surface runoff reported from winter cereals on ploughed land with tramlines of *c.*1 mm to 75 mm (Defra, 2008).
- Sediment losses from conventional maize cropping are in the range of <0.1 to *c.*4 t ha^{-1} and are similar to the range of sediment losses reported from other tillage crops on erodible land, with losses ranging from 0.2 to 5 t ha^{-1} (Broadman 1990; Chambers *et al.,* 1992; Evans 1993 in Chambers and Garwood, 2000; Defra, 2008). Some exceptionally high sediment losses have been reported for maize (at 36 t ha^{-1}, Van Dijk *et al*. (2005)), potatoes and winter cereals (up to 180 m^3 ha^{-1}, Broadman *et al.* (2009)).
- Phosphorus losses from conventional maize cropping are in the range of *c.*0.3 to *c.*4.3 kg ha^{-1}. In comparison, P losses from other tillage crops on erodible land are within the range of 0.01 to *c.*4 t ha^{-1} (Defra project PE0206; Chambers & Garwood, 2000).
- Nitrate leaching losses from conventional maize cropping are in the range of 40-*c.*80 kg NO_3-N ha^{-1} (unpublished results Defra project WQ0140), are comparable to NO_3 leaching losses from potatoes of *c.*70 kg NO_3-N ha^{-1} (Shepherd & Lord, 1996), and mean losses over a 5 year crop rotation are *c.*50 kg NO_3-N ha^{-1} (Johnson *et al*., 2002). As with all crops, it is important that soil nitrogen supply (SNS) is accounted for in order to minimise N-surplus and therefore NO_3 leaching losses.
- From maize sites (project WQ0140) with good soil structure, runoff, sediment, P and NO_3-N leaching losses are within the range reported for other tillage crops.
- Given that almost all of the above ground residue from maize crops is removed it is likely that impacts on SOC contents will be comparable to straw removal.
- The use of pasteurised maize-based digestate on land destined for maize production should not present a risk of crop mycotoxin contamination. Ploughing maize based digestate into the soil is likely to reduce the risks of mycotoxin production by ensuring that Fusarium spore production does not take place on organic matter or on the soil surface (HGCA, 2007).
- Maize has a low biodiversity for both flora and fauna, compared to oilseed rape and sugar beet (Firbank, 2003).

- Project WQ0140 reported that ammonia losses were greater following the application of crop-based digestate (mean losses *c.*30- 50% of N applied) than following cattle slurry (*c.*15 -20% of N applied). This is consistent with the results from the DC-Agri project which concluded that the ammonia emissions from the food-based digestates (*c.*40% of total N applied) compared to livestock slurry (*c.*30% of total N applied). The greater NH_3 emissions from digestate compared to livestock slurry is most likely due to a combination of higher ammonium N contents and elevated pH.

3.1.3 Cover crop mitigation strategies

The impact of cover crops on soil structure, over-winter nutrient and sediment losses and maize productivity has been investigated in England by two studies SP0404 and WQ0140.

In project SP0404, cover crops tested at two sites (North Wyke and Long Ashton in Devon) included: perennial ryegrass (over-sown by broadcasting 1 month after maize drilling), ryecorn (established post-harvest) and clover (broadcast at maize drilling). In WQ0140, over-sown (by broadcasting at the 6-8 leaf stage) ryegrass and biodiverse seed mix (Table 3-3) cover crops were tested at two sites (Norfolk and Devon).

Table 3-3 Species composition of biodiverse seed mix, Defra project WQ0140

Species	Percent by weight	Characteristics
Black medick	20	Spring/autumn germinating, annual or perennial, fairly drought tolerant
Sainfoin	25	Spring germinating, perennial, likely to increase in year 2
Alsike clover	20	Spring/summer germinating, annual or short-lived perennial, establishes and flowers well in year 1
Crimson clover	20	Spring/autumn germinating, biennial or short-lived perennial, early flowering
Bird's-foot trefoil	10	Spring germinating, perennial, likely to increase in year 2
Musk mallow	5	Spring germinating, perennial, tolerates drought

Impacts on soil structural quality

Visual soil structural quality was assessed as part of WQ0140 at sites in Norfolk and Devon using the Peerlkamp method (Section 3.2.1).

In Norfolk there was no difference in the structural quality between the contrasting ground cover treatments (i.e. conventional, strip-tillage-ryegrass and strip-tillage-biodiverse mix). The ST scores from the conventional treatment ranged from 8-9, while from both the strip-tillage-ryegrass and strip-tillage-biodiverse mix treatments, ST scores ranged between 6 and 8 (Figure 3-3).

In Devon, the structural scores from the strip-tillage-ryegrass and strip-tillage-biodiverse mix treatments were consistently 2 points lower than the conventional treatments which had a mean ST score of 9 (Figure 3-4). The lower scores from the strip-tillage treatments were most likely due to compacted soil in the uncultivated strips (which can amount to 40% of the cropped area), in comparison on the conventional treatment any compaction will be alleviated by ploughing and sub-soiling.

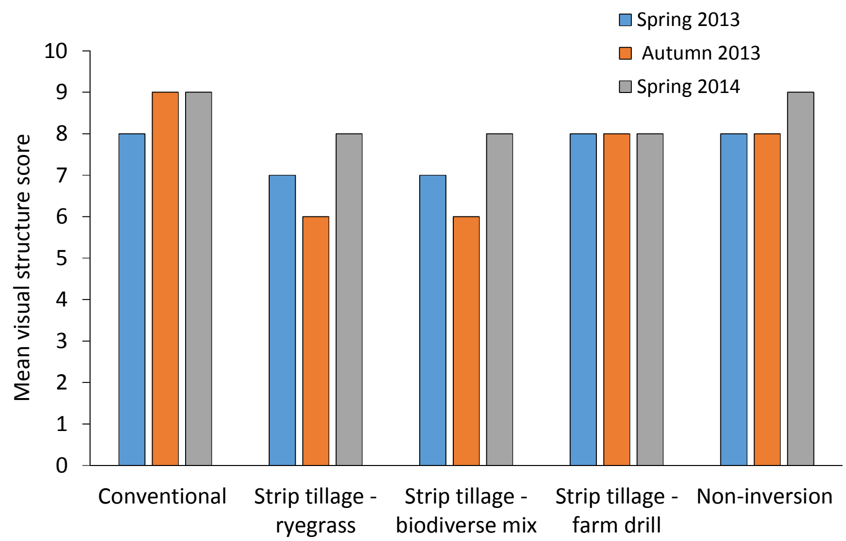


Figure 3-3 Mean visual structure scores measured at Norfolk (Defra project WQ0140) in spring 2013, autumn 2013 and spring 2014. The highest score (10) is given to the least compact and most porous condition, and the lowest score (1) to a massive condition with no structure and few or no cracks.

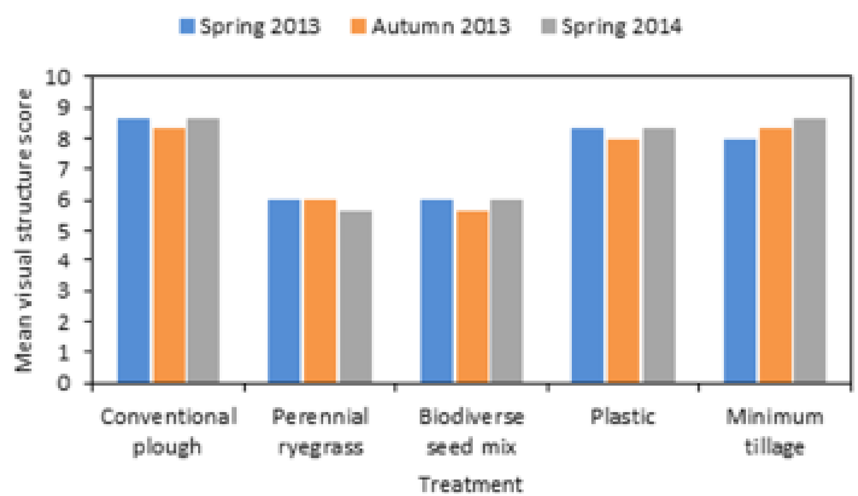


Figure 3-4 Mean visual structure scores measured at Devon (Defra project WQ0140) in spring 2013, autumn 2013 and spring 2014. The highest score (10) is given to the least compact and most porous condition, and the lowest score (1) to a massive condition with no structure and few or no cracks.

Impacts on diffuse Water pollution

The results from SP0404 showed that cover crops sown at or one month after maize drilling were more effective at reducing over-winter diffuse pollution compared to post-harvest established ryecorn. In summary:

- At North Wyke, over-sown ryegrass reduced over-winter runoff by *c.40*-60% and sediment losses by *c.*70%, compared to the conventional stubble treatment.
- At the same site post-harvest drilled ryecorn had variable effects on surface runoff. In one year ryecorn reduced over-winter runoff by 12% compared to the conventional stubble treatment, but more than doubled sediment losses from *c.*700 to *c.*1500 kg ha^{-1}. In another year post-harvest

established ryecorn increased runoff by *c.*15% compared to the conventional stubble treatment. The increase in sediment losses from the post-harvest drilled ryecorn compared to the conventional stubble treatment was a result of the cultivation required to establish the crop.

- At Long Ashton clover reduced over-winter runoff, by *c.*70-90% or by *c.*60-85% (when combined with drilling across the slope) and sediment losses by *c.*85% (when maize was drilled either along or across the slope) compared to the conventional bare stubble treatment.

The diffuse pollution results from WQ0140 demonstrated that, at Norfolk:

- SMN (0-90 cm) levels in November 2012 and April 2013 (Figure 3-5) were lower on the oversown ryegrass ($P<0.01$) than both the conventional and biodiverse mix treatments, reducing the potential for NO_3-N leaching losses.
- Over-winter 2012/2013, NO3-N leaching losses from the oversown ryegrass treatment at 40 kg/ha N were c.50% and c.40% lower (P <0.05) than losses from the conventional and biodiverse mix treatments, respectively, reflecting the differences in SMN levels (Figure 3-5). The lower SMN levels and nitrate leaching losses from the oversown ryegrass treatment were a reflection of N uptake by the well-established ryegrass cover (Figure 3-6), which reduced the amount of soil N compared with the conventional and biodiverse mix treatments.
- Over-winter 2012/2013, sediment losses from the oversown ryegrass treatment at 440 kg/ha were c.70% and c.60% lower (P <0.01) than losses from the conventional and biodiverse mix treatments, respectively (). The reduced sediment losses from the oversown ryegrass treatments is a reflection of the greater ground cover, which slowed down sediment movement, compared with the conventional and biodiverse mix treatments.
- Over-winter 2013/2014 runoff and sediment losses were minimal and there were no differences between the treatments. However, NO_3-N leaching losses from strip-tillage into biodiverse mix and strip tillage into ryegrass were 60% and 70% lower (P =0.01), respectively compared to the conventional treatment (40 kg N ha^{-1}). The reduction in NO_3-N leaching from the strip-tillage ryegrass and strip-tillage biodiverse mix treatments reflected N uptake by the ryegrass and biodiverse mix cover which had been established for *c.*18months.

The results from WQ0140 demonstrated that, at Devon:

- Over-winter 2012/2013, surface runoff losses from the oversown ryegrass treatment at 25 mm were c.40% lower than from the conventional and biodiverse treatments (c.40mm), although these differences could not be confirmed statistically (P>0.05).
- Over-winter 2012/2013, sediment losses from the oversown ryegrass treatment at 140 kg/ha were c.85% and c.75% lower (P <0.01) than losses from the conventional and biodiverse mix treatments, respectively. The reduced sediment losses from the oversown ryegrass treatment were a reflection of the greater ground cover, which slowed down sediment movement, compared with the conventional and biodiverse mix treatments. Notably, the reduction in sediment losses from the ryegrass treatment was greater than the reduction in surface runoff volumes.
- Over-winter 2013/2014 surface runoff losses from the oversown ryegrass treatment at 20 mm and biodiverse mix treatments at 22 mm were c.60% lower than from the conventional treatments (c.50 mm).

- Over-winter 2013/2014 sediment losses from the oversown ryegrass treatment at 67 kg ha-1 and biodiverse mix treatments at 182 kg ha-1 were c.95% and 87%, lower, respectively than from the conventional treatments (c.1375 kg ha-1).

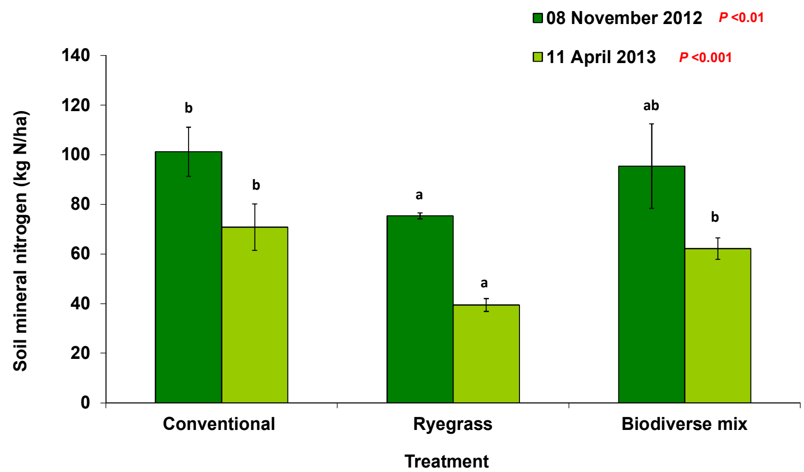


Figure 3-5 Soil mineral nitrogen (0-90 cm) levels measured at Fakenham in November 2012 and April 2013. Error bars represent the standard error of the mean. Bars labelled with different letters, on the same sampling date, differ significantly.

November 2012 | May 2013 | Strip tillage into ryegrass

Figure 3-6 Ryegrass ground cover at Fakenham, oversown in June 2012, following harvest in November 2012 (left) and before (centre) and after strip-tillage (left) in May 2013

Table 3-4 Impacts of over-winter ground cover either on diffuse water pollution

Study	Site	Year of measurement	Soil texture	Field slope (%)	Cultivation method	other treatment details	Over winter ground cover	Rainfall (mm)1	Runoff (mm)	Runoff (% of rainfall)	Sediment loss (kg/ha)	NO3-N leaching loss (kg/ha)	Total P losses (g/ha)
Defra study SP0404	North Wyke	2000	Sandy clay loam	5	conventional	n/a	bare ground	199	43.3	22	719	-	3114
Defra study SP0404	North Wyke	2000	Sandy clay loam	5	conventional	under-sown	under-sown Italian ryegrass	199	16.0	8	213	-	920
Defra study SP0404	North Wyke	2000	Sandy clay loam	5	conventional	post-harvest established	post-harvest established Ryecorn	199	38.1	19	1551	-	5850
Defra study SP0404	North Wyke	2001	Sandy clay loam	5	conventional	n/a	bare ground	340	47.0	14	-	-	-
Defra study SP0404	North Wyke	2001	Sandy clay loam	5	conventional	under-sown	under-sown Italian ryegrass	340	27.1	8	-	-	-
Defra study SP0404	North Wyke	2001	Sandy clay loam	5	conventional	post-harvest established	post-harvest established Ryecorn	340	55.2	16	-	-	-
Defra study SP0404	Long Ashton	1999/2000	Silty clay loam	8	conventional	n/a	bare ground	nd	8.6	nd	33	-	-
Defra study SP0404	Long Ashton	1999/2000	Silty clay loam	8	conventional	clover drilled on same day as maize	clover	nd	2.5	nd	11	-	-
Defra study SP0404	Long Ashton	1999/2000	Silty clay loam	8	conventional	drilled across slope	bare ground	nd	8.1	nd	19	-	-

Table 3 4 (continued) Impacts of over-winter ground cover either on diffuse water pollution

Study	Site	Year of measurement	Soil texture	Field slope (%)	Cultivation method	other treatment details	Over winter ground cover	Rainfall (mm)[1]	Runoff (mm)	Runoff (% of rainfall)	Sediment loss (kg/ha)	NO_3-N leaching loss (kg/ha)	Total P losses (g/ha)
Defra study SP0404	Long Ashton	1999/2000	Silty clay loam	8	conventional	drilled across slope & clover drilled on same day as maize	clover	nd	1.2	nd	3	-	-
Defra study SP0404	Long Ashton	2000/2001	Silty clay loam	8	conventional	drilled across slope	clover	264	2.1	<1	-	-	-
Defra study SP0404	Long Ashton	2000/2001	Silty clay loam	8	conventional	drilled across slope	bare ground	264	4.9	2	-	-	-
Defra study SP0404	Long Ashton	2000/2001	Silty clay loam	8	conventional	n/a	clover	264	1.9	<1	-	-	-
Defra study SP0404	Long Ashton	2000/2001	Silty clay loam	8	conventional	n/a	bare ground	264	22.3	9	-	-	-
Defra WQ0140 study[2]	Norfolk	2012/2013	sandy loam	3	Conventional ploughed	n/a	bare ground	152	2.3	2	1,331	82	1460
Defra WQ0140 study[2]	Norfolk	2012/2013	sandy loam	3	Conventional ploughed	oversown (June 2012)	ryegrass	152	0.6	<1	443	40	330
Defra WQ0140 study[2]	Norfolk	2012/2013	sandy loam	3	Conventional ploughed	oversown (June 2012)	biodiverse mix	152	2.4	2	1,170	65	990

Table 3 4 (continued) Impacts of over-winter ground cover either on diffuse water pollution

Study	Site	Year of measurement	Soil texture	Field slope (%)	Cultivation method	other treatment details	Over winter ground cover	Rainfall (mm)[1]	Runoff (mm)	Runoff (% of rainfall)	Sediment loss (kg/ha)	NO_3-N leaching loss (kg/ha)	Total P losses (g/ha)
Defra WQ0140 study[2]	Norfolk	2013/2014	sandy loam	3	Conventional ploughed	n/a	bare ground	238	0.7	<1	335	40	400
Defra WQ0140 study[2]	Norfolk	2013/2014	sandy loam	3	strip-tillage into ryegrass	oversown (June 2012)	ryegrass	238	0.4	<1	150	12	200
Defra WQ0140 study[2]	Norfolk	2013/2014	sandy loam	3	strip-tillage into biodiverse mix	oversown (June 2012)	biodiverse mix	238	0.4	<1	154	15	200
Defra WQ0140 study[2]	Devon	2012/2013	sandy silt loam	13	Conventional ploughed	n/a	bare ground	425	41.5	10	910	-	1300
Defra WQ0140 study[2]	Devon	2012/2013	sandy silt loam	13	Conventional ploughed	oversown (June 2012)	ryegrass	425	25.2	6	141.5	-	400
Defra WQ0140 study[2]	Devon	2012/2013	sandy silt loam	13	Conventional ploughed	oversown (June 2012)	biodiverse mix	425	42.1	10	624.5	-	1200
Defra WQ0140 study[2]	Devon	2013/2014	sandy silt loam	13	Conventional ploughed	n/a	bare ground	590	51.4	9	1375	-	2440
Defra WQ0140 study[2]	Devon	2013/2014	sandy silt loam	13	strip-tillage into ryegrass	oversown (June 2012)	ryegrass	590	19.9	3	67	-	220
Defra WQ0140 study[2]	Devon	2013/2014	sandy silt loam	13	strip-tillage into biodiverse mix	oversown (June 2012)	biodiverse mix	590	21.6	4	182	-	490

Notes: not measured indicated by '-'; **nd** = no data [1]total rainfall - during surface runoff measurement period, approximately from end of October to end of March; **[2]**Unpublished results from WQ0140

3.1.4 Additional evidence from studies with some relevance to UK maize production

Nitrate leaching

A number of studies carried out in Europe have shown that under-sowing maize can help reduce over-winter NO_3-N leaching losses, as the growing crop takes up mineral-N from the soil which would otherwise be at risk of loss through leaching. In summary:

- Schröder *et al*. (1996), over 6 consecutive years, investigated the effectiveness of post-harvest (mid-September to early-October) established rye and oversown (Early-June) Italian ryegrass to reduce SMN and NO_3 leaching. It was found that for the first 5 years rye and ryegrass took up *c.*46 kg N ha^{-1}, with no difference between species. Nevertheless, ryegrass was consistently more effective at reducing nitrate leaching (Figure 3-7). Notably, in the last year, post-harvest drilling of rye was delayed to early-October, due to wet conditions and the crop failed, taking up <10 kg N ha^{-1}. Schröder *et al*. (1996) also commented that if winter temperature had been closer to long term averages then less N would have been taken up by the cover crops.

- In a combined 3 year field experiment (carried out in Denmark) and modelling study, Manevski *et al.* (2015), found that annual NO_3 leaching (at 31-170 kg NO_3-N ha yr^{-1}) from intercropped maize with red fescue (drilled on the same day) was 15-37 % lower compared to maize alone (45-214 kg NO_3-N ha yr^{-1}).

- Other findings from the annual MGA conference (Peterborough, 2015) Spelling-Ostergaard, presented the results from a study carried out in Denmark (Table 3-5) comparing the effectiveness of different oversown species. In summary it was found that chicory was most efficient at reducing NO_3-N leaching losses. While Finke *et al.* (1999), reported that oversowing maize (when 20 cm high) with grass can reduce the amount of residual nitrate in the soil by harvest and that early sown ryegrass was most effective.

- Whitmore and Schroder (2007) modelled nitrate leaching losses and reported that undersowing maize reduced nitrate leaching by 15 mg/l compared with a rye catch crop and by more than 20 mg/l compared to fallow soil.

Research conducted in the UK investigating the use of cover crops in arable systems suggest that typically, cover crops which are established before the start of drainage are most effective at reducing NO_3 leaching (Davies *et al*., 1996; Shepherd and Lord, 1996). This view is supported by Van Erp & Oenema (1993), who recommend that, for cover crops to be effective they must be established by mid-September. Shepherd and Lord (1996) found that cover crops drilled by mid-September were typically effective at reducing NO_3 leaching with the cover crop taking up between 20-40 kg N ha^{-1}. Möller *et al*. (2011) discuss that the expansion of maize in Germany (for use in biogas digesters) may impact on the extent of cover cropping, as the opportunity for cover cropping is reduced due to the late harvest.

- Davies *et al*. (1996), found that rye sown in early September reduced nitrate leaching by >90% (equivalent to 28 kg N ha^{-1} yr^{-1}) compared to losses from bare ground. However, when the onset of drainage began in late-September compared to late-December, rye was less effective at reducing NO_3 leaching losses (23% reduction compared to losses from bare ground); this was because N uptake before the start of drainage was minimal (Davies *et al*., 1996).

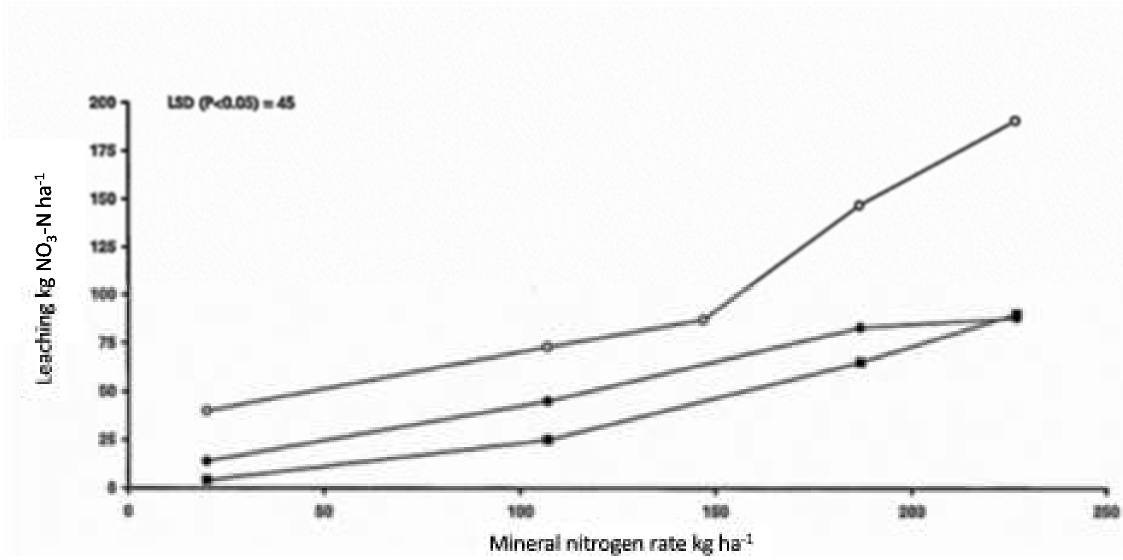


Figure 3-7 Relationship between the summed input of soil mineral N in spring (0.6 m layer), fertiliser N and NH_4-N in slurry applied to maize and N leaching during winter (average from 1988-1989 to 1993) as affected by cover crops (○ = fallow, ● = rye ■ = grass) (taken from Schröder et al.*, 1996).*

Surface runoff and sediment losses

A number of European studies have demonstrated that planting maize into over-winter cover crops can alleviate soil erosion and surface runoff. For example, Hall *et al*. (1984) showed that 'living mulches' of birdsfoot trefoil reduced soil erosion, surface water runoff and cyanazine herbicide losses on sloping land growing corn more effectively than corn (stover) residues alone. Compared to conventional cultivation, untilled corn residue and living mulch reduced surface runoff by 86-99 % and sediment losses by 97 - 100%. Further research conducted at various locations in Switzerland demonstrated that sowing maize in over-winter cover crop residues of rye and mustard (killed by frost or herbicides), in conjunction with minimum tillage, was a very effective means of controlling soil erosion and agrochemicals losses in surface run-off (Ruttimann *et al*., 1995). It was found that rye and mustard cover-crops reduced surface runoff by a factor of 3 and sediment loss by a factor of more than 10 compared to the conventional treatment, with no difference between cover-crop species.

A survey monitoring soil erosion across Switzerland over 10 years, found that the highest rates of soil erosion took place in potato (2.87 t ha^{-1} yr^{-1}), followed by fallow (1.06 t ha^{-1} yr^{-1}) and winter wheat (1.05 t ha^{-1} yr^{-1}) fields. Soil erosion from maize fields was below average at 0.44 t ha^{-1} yr^{-1} with erosion in maize accounting for only 10% of the total soil lost. The lower rate of soil erosion from maize was attributed to establishing maize by strip-tilling into grass-clover (Prasuhn *et al.*, 2012).

Laloy and Bielders (2010) reported that over-winter surface runoff was less than 2 mm following post maize harvest non inversion cultivation (0- 15 cm) and rye winter cover crop; in comparison, from maize stubble, runoff was between *c.*57 to *c.*66 mm. However, it is difficult to know if the reduction in surface runoff were due to post-harvest cultivation alone. Furthermore, Kwaad *et al.* (1998) reported that the use of a winter rye cover crop did not lead to the reduction of surface runoff above the effect of the autumn ploughing. Over-winter (1991-1992) runoff from the ploughed with/ without rye cover ranged from *c.*1.9 to 3.8 mm in comparison, runoff from maize stubble was *c.*81 mm. Over-winter (1992-1993) runoff from the ploughed with/ without rye cover ranged from *c.*0.94 to 1.8 mm in comparison, runoff from maize stubble was *c.*22 mm.

Impacts of ground cover on invertebrate biodiversity

In Defra project WQ0140, the impacts of oversowing maize and retaining the ground cover by establishing the subsequent maize crop using strip-tillage cultivation, on invertebrate biodiversity has been investigated. At both the Norfolk and Devon sites, maize was oversown (in June 2012) with either ryegrass or a biodiverse seed mix (Table 3-5); in the following two harvest years (2013 & 2014) maize was establishment by strip-tilling into the established ground cover. Assessments included sampling of below-ground invertebrates (mesofauna, macrofauna and earthworms) above-ground invertebrates and bumblebee transects.

Below-ground invertebrate biodiversity

Overall at both sites, it was found that below-ground invertebrate richness was significantly (P <0.05) higher in the strip-tilled-biodiverse mix treatment (mean = 17) compared to all other treatments (Table 3-5). There was no significant difference (P >0.05) in the abundance of below-ground invertebrates between the strip tilled-ryegrass and biodiverse mix treatments (Table 3-5). Notably, the abundance of below-ground invertebrates from the strip tilled-biodiverse mix and ryegrass (overall mean = 14,592 individuals m^2) was *c.*55% (P <0.05) greater than the conventional and non-inversion cultivation treatments.

Table 3-5 Below ground invertebrate mean family richness and invertebrate abundance (m^2) for each cultivation method, values in parenthesis represent the standard error of the mean.

Cultivation Method	Mean Richness	Mean Abundance (Individuals m^2)
Conventional plough	12 (0.50)	7,030 (887)
Strip tillage-ryegrass	15 (0.75)	15,292 (1,910)
Strip tillage-biodiverse seed mix	17 (0.93)	13,892 (1,893
Non-inversion	12 (0.57)	5,823 (582)

Above-ground invertebrate biodiversity

Overall at both sites, the above-ground biodiversity results were consistent with the findings of the below-ground biodiversity assessments. Above-ground invertebrate richness was significantly higher (P <0.05) in the strip tilled-biodiverse mix treatment (mean richness = 21) compared to all other treatments (Table 3-6).

There was no significant difference (P >0.05) in the density of above-ground invertebrates between the strip tilled-ryegrass and biodiverse mix treatments (Table 3-6). The abundance of above-ground invertebrates from the strip tilled-biodiverse mix and strip tilled-ryegrass (overall mean =363) was *c.*25% (P <0.05) greater compared to the conventional and non-inversion cultivation treatments.

Table 3-6 Above ground invertebrate mean family richness and invertebrate density for each cultivation method, values in parenthesis represent the standard error of the mean.

Cultivation Method	Mean Richness	Mean Density
Conventional plough	15 (0.53)	269 (25)
Strip tillage-ryegrass	18 (0.63)	351 (33)
Strip tillage-biodiverse seed mix	21 (0.59)	374 (28)
Non-inversion	16 (0.59)	267 (25)

Bumblebee biodiversity

At both sites, measurement of bumble populations showed that both bumblebee richness and density was significantly (*P* <0.05) greater on the strip tilled-biodiverse mix treatment compared to all other treatments (Table 3-7). Notably on all other treatments a near complete absence of bumblebees was recorded.

Table 3-7 Bumblebee mean species richness and density for each cultivation method, values in parenthesis represent the standard error of the mean.

Cultivation Method	Mean Richness	Mean Density
Conventional plough	0 (0.04)	0 (0.1)
Strip tillage-ryegrass	0 (0.05)	0 (0.1)
Strip tillage-biodiverse seed mix	2 (0.15)	18 (2.4)
Non-inversion	0 (0.04)	0 (0.1)

Summary of impacts of ground cover on Invertebrate biodiversity

- Strip –tillage with ground cover increased the biodiversity of below-ground invertebrates
- Strip-tillage with ground cover increased the biodiversity of above-ground invertebrates
- Strip-tillage –biodiverse mix increased the biodiversity of bumblebees.

3.1.5 Management strategies for establishing cover crops in maize

Given the late maize harvest (late-September to early-November) in the UK and difficulties in establishing a cover crop in late-autumn/early-winter, oversowing is one approach of ensuring ground-cover immediately following maize harvest. However, it is important that effective oversowing management strategies are devised that mitigate diffuse water pollution (e.g. NO_3 leaching, sediment and P losses) whilst not having a detrimental impact on crop yields.

Strip-tillage into existing ground cover -impacts on maize productivity

In the UK Defra funded projects SP0404 and WQ0140, assessed the impact of ground cover on maize yields.

In project SP0404, there was no significant difference in maize dry matter yields between conventional and over-sown ryegrass treatments, *i.e. only a 4% reduction*. However, it was found that broadcasting clover at maize drilling significantly reduced yields by *c.*40-50% compared to the conventional treatment, the reductions in maize yield was attributed to plant competition, from broad-leaved weeds in the inter-row.

In project WQ0140 in all site years, maize yields were significantly reduced when established by strip-tilling into either ryegrass (Figure 3-6) or a biodiverse mix ground cover by up to *c.*90% (in harvest year 2013) or *c.*50% (in harvest year 2014) compared to the conventional treatment. Maize yields were reduced due to increased plant competition for water and nutrients at the early stages of maize growth.

Developing over-sowing management strategies

Research carried out in Denmark, has assessed the impact of soil type, cover-crop species, oversowing timing and method on, cover crop establishment, maize yields and NO_3 leaching. Hans Spelling Oestergaard, presented results from a recent research project carried out in Denmark, at the annual Maize Growers Conference (Peterborough, February 2015), the key findings are summarised in Table 3-8.

Table 3-8 Summary of key findings of research investigating management strategies for over-sowing maize conducted by SEDGES (Demark) presented at the annual Maize Growers Conference (Peterborough, February 2015) by Spelling Oestergaard.

Parameter	Overall finding
Cover crop species	Chicory, perennial ryegrass, Italian ryegrass, cocks foot and tall fescue might reduce maize yields if sown early (before mid-June) especially on low fertility soils. Tall fescue is best suited for early sowing (before mid-June). Chicory can be sown late because it can tolerate shading below the maize canopy. Perennial ryegrass and Italian ryegrass are best suited for late sowing. A mixture of perennial ryegrass and chicory is also suitable for late sowing.
Impact on Yield	Early or late oversown cover crops did not significantly impact on maize yields, however there was a tendency for small reductions in maize yields, on soils with low or medium fertility. Oversowing at the same time as maize drilling significantly reduced yields on soils with low fertility but not on soils with high fertility (e.g. previous crop grass with clover).
Methods of sowing	It was found the two best methods to ensure fast and high germination were ranked: 1. Strip sowing (3 rows) to 1-2 cm depth and a firm soil leaving 20 cm between cover crop and maize. 2. Strip sowing 3 rows with a hoe and then covering with loose soil. The least effective method was: 3. Surface broadcast of seeds then covering with loose soil by hoeing.
Nitrate leaching	It was found that chicory was the most efficient at reducing NO_3-N leaching.

The results demonstrate that slower growing grasses such as tall fescue were best suited to early oversowing (before mid-June) whereas chicory which is faster growing can be oversown later becoming established before being shaded by the maize canopy. Drilling 3 rows of cover crop and leaving 20 cm between the maize row and cover crop was the most effective method, i.e. ensures a fast and high rate of germination. Overall, early or late oversowing did not have a significant detrimental impact on maize yields, but there was a tendency for small reductions in maize yields on low to medium fertility soils.

This finding is consistent with other studies which have reported that maize crop yields are not necessarily reduced by oversowing grass or leguminous cover crops as long as seeding is not too early (Abdin *et al*. 2000; Finke *et al*., 1999; Kramberger *et al*., 2009). Hall *et al*. (1984) reported that corn grain yields were not significantly reduced by 'living mulches', when adequate legume suppression was obtained with herbicide treatments, whilst Garibay *et al.* (1997) suggested that changing the botanical composition and management of cover crops could help reduce competition for nitrogen.

Post winter cover-crop management strategies in continuous maize systems

It is important to develop strategies for managing the over-winter ground cover to ensure the yields of any subsequent maize crops are not reduced. Data from project WQ0140 has demonstrated over 4 site years that establishing a maize crop by strip-tilling into ground cover can sustainably reduce maize yields. Research conducted elsewhere in Europe, has investigated the effectiveness of alternative strategies for establishing maize after over-winter ground cover:

- Kramberger *et al.* (2014), sowed (at the end of August) cover crop mixes of ryegrass and crimson clover following winter wheat harvest, and in the following spring tested 3 contrasting strategies to manage the cover crops before sowing maize. Strategies included: 1) cover crop biomass was ploughed in before seedbed preparation and sowing, 2) cover crop was harvested before ploughing, seedbed preparation and sowing and 3) the cover crop was harvested, stubble chemically killed and the maize directly sown without any soil cultivation. Overall, the results indicate that either ploughing in the cover crop or taking a cut and then ploughing were the most effective management approaches, in comparison, chemically killing the cover crop and direct drilling of the maize reduced yields by *c.*30%. The study also found differences between cover crop species, maize yields were *c.*25% lower following a cover crop of ryegrass compared to crimson clover.
- Ruegg *et al*. (1998) reported that silage maize yields were decreased when maize was drilled using strip tillage techniques into stubble of forage rye due to either low crop available N supply or to unfavourable soil conditions following non-inversion cultivation.

Buffer strips

Establishing unfertilised grass buffer strips along contours, in valley bottoms or on upper slopes can help reduce surface runoff, sediment and total P losses and help improve biodiversity. Defra project PE206 reported that 2 m wide buffer strips reduced suspended sediments and total P losses by 9-97% (Defra, 2005) and significantly reduced suspended sediment and total P losses, in both years of the experiment, from conventionally-ploughed soils by 32-97%.

The Mitigation User Guide (Newell Price, *et al*., 2011) states grass buffer strips are most suited to fields with long slopes where high volumes of surface runoff can be generated and can be effective at reducing P and associated sediment by 20-80 %. The buffer strips should be managed to reduce risks of weed growth.

Summary of mitigation potential of cover crops

The results demonstrate that, the effectiveness of cover crops to reduce runoff, sediment, total P and NO_3 leaching losses varies with the timing and method of establishment and cover-crop species:

- Project SP0404 & Kwaad *et al.* (2008) demonstrated, that post-harvest established ryecorn had a minimal impact on reducing surface runoff. Furthermore, establishing ryecorn after maize harvest, more than doubled sediment losses to 1551 kg ha^{-1} compared to the conventional treatment at North Wyke (SP0404). The project concluded that this was due to a loosening of the soil surface associated with cultivating in order to establish the cover crop.
- White clover at Long Ashton (SP0404) was effective at reducing over-winter runoff by up to 90% and sediment losses by up to 85%. However, in project WQ0140 there was no difference in over-winter runoff, sediment, total P and NO_3 leaching losses between the biodiverse seed mix (6 months after establishment) and conventional (plough-based) cultivation treatments.

- Project SP0404 showed that ryegrass oversown approximately 1 month after drilling reduced over-winter diffuse runoff by to 60% and sediment losses by up to 70% compared to the conventional treatment of bare ground.
- Project WQ0140 showed that at the Norfolk site, oversown ryegrass, 6-months after establishment, reduced over-winter NO_3-N leaching losses by 50%, and sediment losses by 70%, compared to the conventional treatment of bare ground. This finding is consistent with previous research, which has demonstrated that cover-crops are most effective at reducing NO_3-N leaching when drilled by late August to early-September (Davies *et al*., 1996; Shepherd and Lord 1996). At Bow oversown ryegrass, 6-months after establishment, reduced over-winter runoff by 40% (although these results could not be confirmed statistically), and sediment losses by 80%, compared to the conventional treatment of bare ground.

Despite the potential for oversown cover crops to reduce runoff, sediment, total P and NO_3 leaching losses, the main challenge is to limit the competition between ground cover and maize at the early stages of development to ensure there is no detrimental impact on maize yields.

- WQ0140 demonstrated that it is not practical to retain the ground cover in the following spring and establish a maize crop by strip-tilling into a growing ground cover, because of yield reductions up to 90% compared with convention maize production.
- Project SP0404 showed that, establishing white clover at maize drilling, significantly reduced maize yields in both harvest years 1999 and 2000, with mean reductions of *c.*50% and 40%, respectively.
- There is limited evidence from the UK available on the impacts of oversowing on maize yields. However, the results from SP0404 indicate that any reductions are not significant (i.e. *c.*4%).

In maize cropping oversowing is one technique which can establish a cover crop that is effective at reducing surface runoff, sediment, P and NO_3 leaching losses. It is important that management strategies for oversowing maize grown in the UK are implemented, which ensure: 1) that the cover crop germinates before the maize canopy closes, otherwise it will not establish due to shading, 2) that the cover crop does not compete with the maize crop at the early stages of development, which could result in a reduction in crop yield and 3) in continuous maize rotations any cover crops should be managed to ensure there is no detrimental impact on subsequent maize crop yields.

3.1.6 Soil management – mitigation strategies

Reduced tillage

Both Defra funded studies SP0404 and WQ0140 have investigated the effects of reduced tillage (i.e. non-inversion cultivation or strip-tillage) on the environmental impacts of maize production. Strip tillage is the cultivation of narrow bands of soil directly into crop stubble or into sown crops. Depending on the machinery used the cultivated band is approximately 30cm wide and the uncultivated strip 45cm wide. Generally with strip tillage approximately 50-70% of the field is left uncultivated.

Impacts on soil structural quality

The effects of reduced cultivation on soil structural quality were assessed as part of WQ0140. Peerlkamp visual soil structure assessments (Section 0) were conducted at 2 sites (Norfolk and Devon) on conventional and non-inversion or strip-tillage (into bare ground) treatments, at 0-20cm depth, in spring 2013, autumn 2013 and spring 2014; overall, at both sites, no differences in soil structural quality were reported across the contrasting cultivation treatments (Figure 3-3 & Figure 3-4).

Impacts on diffuse water pollution

The impacts of reduced cultivation on runoff and diffuse water pollution (sediment, total P and NO_3 leaching losses) are summarised in Table 3-9, in summary:

- SP0404 - compared conventional plough-based with non-inversion cultivation on a silty clay loam soil at Long Ashton in Devon (1998/1999). Overall the study concluded that were no differences in diffuse water pollution (runoff and sediment losses) from non-inversion compared to conventional cultivation.
- WQ0140 - at Devon (2013/2014), compared conventional plough-based with non-inversion cultivation on a sandy silt loam soil. The study found no significant differences in over-winter surface runoff, sediment losses or total P losses between conventional and non-inversion cultivation techniques.
- WQ0140 –at Norfolk (2013/2014), compared conventional plough-based with non-inversion cultivation and strip-tillage (into bare ground) on a sandy loam soil. Over-winter runoff volumes were negligible from all treatments. There was no significant difference in over-winter NO_3-N leaching losses between conventional and non-inversion or strip-tillage (into bare ground) treatments ($P > 0.05$).

Post-harvest chisel ploughing

As maize is typically harvested from late September (at the earliest for early maturing varieties) to early November, it is often too late to establish winter combinable crops following harvest. Following the implementation of the new Good Agricultural Environmental Condition Standards (GAECs), post-harvest cultivation for maize has been identified as an effective approach to minimise soil erosion to comply with GAEC 5 "Minimum land management reflecting site specific conditions to limit erosion". In England, the impacts of post maize harvest cultivation on diffuse pollution have been investigated in two studies Defra funded project SP0404 and Withers and Bailey (2003). In summary the results show:

- Data from SP0404 (on sandy clay loam soil), showed that chisel ploughing when soils were dry helped to reduce over-winter surface runoff to <0.1mm and sediment losses to <10 kg/ha in comparison surface runoff was *c.*40mm and sediment losses *c.*700 kg/ha on maize stubble. Chisel ploughing increased the surface roughness which reduced runoff by helping water to percolate down into the soil. However, on a silty clay loam soil, chisel ploughing was not effective at reducing over-winter runoff compared to conventional stubble over-winter increased surface runoff from *c.*22 mm to *c.*33 mm. The greater runoff on the chisel ploughed treatment indicate that soil conditions were not suitable for cultivation.
- Withers & Bailey (2003) showed that, in two out of three years post-harvest cultivation reduced surface runoff by *c.*50% compared to uncultivated maize stubble, indicating that surface roughness as a result of cultivation helped to increase water infiltration. Post-harvest cultivation had little impact on sediment losses compared to maize stubble in two out of three years. In the third year, mean sediment losses following post-harvest cultivation were greater at 6.80 g L^{-1} than from uncultivated maize stubble (*c.*5.60 g L^{-1}), these differences arose in the first storm event. The study showed that, whilst reductions in surface runoff were noticeable through the whole monitoring period the effects became less obvious during intense rain storms.

In summary, the evidence indicates that post-harvest chisel ploughing can be effective at reducing surface runoff and sediment losses when soil conditions allow.

Table 3-9 Impacts of reduced cultivation (i.e. non-inversion or strip-tillage cultivation) on diffuse water pollution

Study	Site	Year of measurement	Soil texture	Field slope (%)	Cultivation method	other treatment details	Rainfall (mm)[1]	Runoff (mm)	Runoff (% of rainfall)	Sediment loss (kg/ha)	NO_3-N leaching loss (kg/ha)	Total P losses (g/ha)
Defra study SP0404	Long Ashton	1998/1999	Silty clay loam	8	conventional	n/a	nd	33.7	nd	1,379	-	2,055
Defra study SP0404	Long Ashton	1998/1999	Silty clay loam	8	Non -inversion	n/a	nd	54.2	nd	2996	-	4,239
Defra study SP0404	Long Ashton	1998/1999	Silty clay loam	8	Non-inversion	drilled across slope	nd	31.7	nd	647	-	1,549
Defra study SP0404	Long Ashton	1998/1999	Silty clay loam	8	Non-inversion	narrow rows	nd	59.4	nd	2,560	-	4,384
Defra study SP0404	Long Ashton	1998/1999	Silty clay loam	8	Non-inversion	narrow rows & drilled across slope	nd	26.9	nd	2,302	-	2,407
Defra WQ0140 study[2]	Norfolk	2013/2014	sandy loam	3	conventional	n/a	238	0.7	<1	335	40	400
Defra WQ0140 study[2]	Norfolk	2013/2014	sandy loam	3	strip-tillage using farm drill	n/a	238	0.5	<1	312	30	300
Defra WQ0140 study[2]	Norfolk	2013/2014	sandy loam	3	non-inversion	n/a	238	0.7	<1	338	48	500
Defra WQ0140 study[2]	Devon	2013/2014	sandy silt loam	13	Conventional ploughed	n/a	590	51.4	9	1375	-	2440
Defra WQ0140 study[2]	Devon	2013/2014	sandy silt loam	13	non-inversion	n/a	590	42.1	7	1150	-	2040

Notes: not measured indicated by '-'; **nd** = no data[1]total rainfall - during surface runoff measurement period, approximately from end of October to end of March; [2]Unpublished results from WQ0140

Table 3-10 Impacts of post-harvest chisel ploughing on diffuse water pollution

Study	Site	Year of measurement	Soil texture	Field slope (%)	Cultivation method	Rainfall[1] (mm)	Runoff (mm)f	Runoff (% of rainfall)	Sediment loss (kg/ha*) or when indicated by *g L^{-1}*	Total P losses (g/ha)
Defra study SP0404	North Wyke	2000	Sandy clay loam	5	conventional stubble over-winter	199	43.3	22	719	3114
Defra study SP0404	North Wyke	2000	Sandy clay loam	5	Post-harvest chisel ploughed	199	0.1	<1	9	41
Defra study SP0404	North Wyke	2001	Sandy clay loam	5	conventional stubble over-winter	340	47.0	14	-	-
Defra study SP0404	North Wyke	2001	Sandy clay loam	5	Post-harvest chisel ploughed	340	23.1	7	-	-
Defra study SP0404	Long Ashton	2000/2001	Silty clay loam	8	conventional stubble over-winter	264	22.3	9	-	-
Defra study SP0404	Long Ashton	2000/2001	Silty clay loam	8	Post-harvest chisel ploughed	264	33.1	13	-	-
Withers and Bailey (2003)	Devon	1998/1999	Sandy loam	nd	conventional stubble over-winter	157	1.63	1	0.56*	-
Withers and Bailey (2003)	Devon	1998/1999	Sandy loam	nd	Post-harvest ploughed	157	1.43	<1	0.22*	-
Withers and Bailey (2003)	Devon	1998/1999	Sandy loam	nd	Post-harvest tine cultivation	157	1.52	<1	0.28*	-
Withers and Bailey (2003)	Devon	1999/2000	Sandy loam	nd	conventional stubble over-winter	334	27.5	0	2.35*	-
Withers and Bailey (2003)	Devon	1999/2000	Sandy loam	nd	Post-harvest ploughed	334	14.3	4	2.20*	-
Withers and Bailey (2003)	Devon	1999/2000	Sandy loam	nd	Post-harvest tine cultivation	334	14.2	4	2.19*	-
Withers and Bailey (2003)	Devon	2000/2001	Sandy loam	nd	conventional stubble over-winter	274	59.7	22	2.92*	-
Withers and Bailey (2003)	Devon	2000/2001	Sandy loam	nd	Post-harvest ploughed	274	26.0	9	6.80*	-
Withers and Bailey (2003)	Devon	2000/2001	Sandy loam	nd	Post-harvest tine cultivation	274	33.7	12	5.61*	-

Notes: not measured indicated by '-'; **nd** = no data**;** [1]total rainfall - during surface runoff measurement period, approximately from end of October to end of March

Additional evidence from studies with some relevance to UK maize production

For maize, the effectiveness of post-harvest management options will be controlled by soil type and conditions at the time of cultivation. Post-harvest management options to reduce soil degradation are limited, due to limited plant growth potential in late autumn/ winter. Balshaw *et al*. (2013) concluded that typically, the most appropriate post-harvest management strategy is to create a rough soil surface to encourage surface water infiltration, which reduces the risk of surface runoff, erosion and associated losses of sediment and particulate P (Newell Price *et al.,* 2011).

Creating a rough soil surface by ploughing or discing has been found to be a useful soil management method for reducing surface runoff volumes, but can have variable impact in relation to particulate P and nitrate-N losses (Angle *et al*, 1993; Benham *et al*, 2007; Kay *et al*, 2009). Newell Price *et al*. (2011) indicate that particulate P and associated sediment losses can be reduced by up to 80%. While Zeiman *et al*. (2006) suggested that the transport of soluble P in surface runoff could be reduced by a factor of 2-3 through rough surface compared to an untilled surface. Laloy and Bielders (2010) reported that, over-winter surface runoff was <10 mm following non-inversion cultivation (0-15 cm) post maize harvest. Furthermore, caution should be taken on erosion-susceptible soils - fine, rolled seedbeds should be avoided as these soils will be most prone to slaking and capping which will lead to increased risks and rates of surface runoff and soil erosion (Chambers *et al*., 2000).

Cultivating and drilling across the slope

Cultivating across the slope increases down-slope surface roughness, reducing the risk of surface runoff, particulate P and associated sediment and where runoff does occur increases re-deposition rates (Newell Price *et al.*, 2011).

The Defra funded project SP0404 found limited evidence that drilling maize across the slope reduced surface runoff and sediment losses. On one site, preparing the seedbed and drilling maize across the slope reduced surface runoff by 40% compared to cultivating and drilling up and down the slope. A white clover understorey plus drilling across the slope reduced water runoff by *c.*90%, however the clover understorey significantly reduced maize yields (Section 3.1.5)

Additional evidence from studies with some relevance to UK maize production

The effects of cultivating or drilling across the slope are unclear. Some studies have reported that cultivating or drilling across the slope can reduce sediment and P losses (soluble and particulate) from fields *with simple sloping patterns* (Defra, 2009; Quinton, 2004 & Defra, 2008b). Deasy *et al*. (2010), reported that contour cultivation reduced runoff by 69-76% and suspended sediment by 45-79%. However, Stevens *et al. (*2009) found that while contour cultivation helped to increase surface roughness, there was no significant difference in surface runoff and sediment losses compared to up and down slope cultivation in both plough-based and minimal tillage cultivation (Balshaw *et al*., 2013).

The limited available evidence suggests that cultivating and drilling across the slope reduces sediment and P-losses by 40-80% (Balshaw, *et al*., 2013). However, the Defra code of Good Agricultural Practice (2009) highlights that this method is only likely to be effective on gently to moderate sloping fields with simple sloping patterns. On steeper soils, cultivating across the slope often leads to channelling of surface waters particularly in tramlines and wheelings, which can result in rills and gully erosion (Quinton and Catt, 2004; Deasy *et al.*, 2010; Balshaw, *et al*., 2013). Maetens *et al.* (2012) concluded that vegetation management techniques (e.g. buffer strips and cover cropping) are generally more effective at reducing surface runoff and sediment losses than soil management techniques (i.e. no-tillage, reduced tillage and contour tillage).

Summary of the mitigation potential of soil management practices

- Overall, in project WQ0140, neither non-inversion nor strip-tillage cultivation, demonstrated any significant impacts in reducing diffuse water pollution.
- When soil conditions are appropriate, chisel ploughing post maize harvest can be effective at reducing surface runoff and sediment losses (Defra project SP0140; Withers and Bailey, 2003). However, there is a risk that soil conditions post maize harvest may not be suitable for cultivation, especially if crops are harvested late (i.e. October/November) and soils are wet.

3.2 Environmental costs and benefits of maize use

Alongside the environmental impacts of maize production, there are potential environmental impacts (costs) and benefits through its use. Two primary uses of maize are for bioenergy and livestock feed.

3.2.1 Maize use for bioenergy

In this section we review the benefits and impacts of maize use for bioenergy. Table 3-11 shows the production stages covered by this section. This will cover the GHG emissions savings potential of electricity and heat production, and wider environmental impacts of the AD process.

Table 3-11 Maize AD production stages

Covered by this task				
Production stage	maize storage at AD plant	AD process	digestate/ waste storage	waste disposal
Output 1	Local environmental impacts on air, water, soil, biodiversity for steps of the chain covered.			
Output 2	GHG emissions for whole bioenergy production chain, compared with GHG emissions for counterfactual			
Input to other tasks				quantities for disposal to landfill

The main use of maize for energy production is as a feedstock for anaerobic digestion (AD) to produce biogas for heat and/or electricity generation. Whole-crop maize is used as a feedstock for AD, and maize silage is the preferred feedstock as this is easy to store on farm and has good biogas feedstock characteristics. The main criterion for choice of variety is high biomass yield.

Currently the majority of AD plants in the UK produce electricity, with 24 claiming Renewable Obligation Certificates (ROCS) and 107 claiming Feed in Tariff (FITS) in 2014. The size range of UK AD plants is from about 100kWe to 5MWe[15]. However, there is increasing interest in upgrading the biogas produced (which typically contains 60% methane, 40% CO_2 and a range of impurities) to biomethane. Upgrading involves removal of almost all the CO_2 and impurities and produces a gas that has a suitable composition for injection into the UK Gas Grid or utilisation as a transport fuel. RHI statistics show that in January 2015 four biomethane installations were receiving payments[16], and Green Gas Grids claim that there are six operational biomethane to grid (BTG) plants in the UK.

[15] Biomethane for transport from landfill and anaerobic Digestion. Ricardo-AEA for DfT, February 2015

[16] Non domestic RHI and domestic RHI monthly deployment data: January 2015

There are currently a range of feedstocks used for AD in the UK. Table 3-12 is taken from a recent NNFCC report[17] and shows the feedstocks used in current operational AD plants. Although the largest feedstock sources are waste derived, there is a considerable contribution from crops, which will include maize. In addition the NNFCC report predicts that crop use for AD will increase significantly in the future. Although use of crops for AD has fewer environmental advantages than use of waste feedstocks, there are a number of reasons why the use of crops is advantageous. These include:

- Security of supply- maize can be home grown or bought on the commodity market.
- Improved performance of AD plant. In particular addition of a proportion of maize to slurry based AD systems improves digester performance.
- Introduction of maize into farm rotations can be advantageous from a farm business perspective.

Table 3-12 Quantities of feedstocks used in current operational AD plants (taken from NNFCC report, 2014)

	Manure/Slurry (Tonnes per annum)	Food Waste (Tonnes per annum)	Crops (Tonnes per annum)	Crop/Agricultural Residues (Tonnes per annum)	Other Wastes (Tonnes per annum)
Scotland	15,000	126,000	35,500	0	175,500
Wales	15,000	32,000	11,500	5,500	35,500
N. Ireland	69,500	15,000	66,000	0	40,000
England	351,000	1,265,000	639,000	183,000	462,500

GHG emissions savings potential of energy production from AD using maize as a feedstock.

The UK Solid and Gaseous Biomass Carbon Calculator (Carbon Calculator) published by Ofgem has been developed to calculate GHG emissions from a number of electricity and heat production routes relevant to the ROC, FIT and RHI schemes administered by Ofgem. The Carbon Calculator utilises a methodology compliant with the Renewable Energy Directive (RED) and is based on UK specific information[18]. The latest version of the Carbon Calculator includes both production of electricity from AD and production of bio-methane for grid injection from AD. Maize can be selected as a feedstock in both cases. The Carbon Calculator has therefore been used to estimate GHG emissions from these processes.

[17] NNFCC 2014. Anaerobic digestion deployment in the UK. http://www.nnfcc.co.uk/bioenergy/ad-deployment-report

[18] The latest version (version 2, build 34) is available to download from the Ofgem website. https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator

Table 3-13 & Table 3-14 show the default values used in the Carbon Calculator for some of the main parameters of interest. All the default parameters can be viewed within the Carbon Calculator.

Table 3-13 Maize production parameters

Parameter	Model default value
Maize Yield, fresh tonne/ha	56.67
Fertiliser input	
N, kg nutrient/ha	27
K, kg nutrient/ha	83
P, kg nutrient/ha	41
digestate, tonnes/ha	100

Table 3-14 Biomethane losses in system

Process	Loss assumed in Model
Biogas production	0.2gCH4/MJ biogas
Biogas upgrading to biomethane	0.2gCH4/MJ biomethane
Biomethane injection to grid	0
Combustion of biogas	0

For the case of AD of slurry, no allowance has been made in the Carbon Calculator for the reduced emissions from digestate as opposed to raw slurry.

The carbon calculator has also been used to estimate the GHG emissions from a CHP system based on combustion of wood chips, and a biomethane production system based on gasification of wood chips. The GHG emissions for these systems are shown for comparison with the emissions using AD technology.

Table 3-15 shows the GHG emissions in units of gCO_2eq/MJ output from the AD systems on the left of the table, and the other technologies on the right of the table. The AD technologies shown are CHP and biomethane production, using maize as feedstock and wet manure as feedstock.

For AD systems, the first rows of the table show the contributions to the GHG emissions from the various stages of feedstock production/ collection and processing to produce biogas. For the biomethane options the GHG emissions associated with upgrading and injection the biomethane to the grid are then shown. For the CHP option, the total emissions allocated to each MJ electricity production are shown. These take into account the efficiency of electricity and heat production from biogas and the allocation of emissions between electricity and heat in the CHP system.

A similar format is followed for the other technologies.

Table 3-15 Greenhouse gas (GHG) emissions (gCO_2eq/MJ) output from AD systems and other technologies

GHG emissions per MJ energy output

	Using AD technology, gCO_2eq/MJ output				Using combustion technology, $kgCO_2eq/t$ wood fuel	Using gasification technology, gCO_2eq/MJ biomethane
	CHP from maize silage	**Biomethane from Maize silage**	**CHP from wet manure**	**Biomethane from wet manure**	**CHP from wood residues**	**Biomethane from wood residues**
Crop production	15.3	15.4				
Harvesting and extraction	0.8	0.8			3.2	0.3
Production of silage /wood chipping	2.0	2.0			4.3	0.4
Transport	1.1	1.1	2.5	2.5	15.2	0.7
Biogas production plant	6.4	6.5	6.2	6.3		
TOTAL/ MJ biogas production	*25.7*	*25.9*	*8.7*	*8.8*		0.0
TOTAL/t wood fuel production					*22.6*	
Upgrading		11.9		11.9		
Gas Injection to grid		2.4		2.4		2.4
TOTAL/MJ biomethane production		**40.1**		**31.9**		**3.7**
Total/MJ electricity production (allowing for conversion efficiency of 38% electricity , 42% heat)	**48.5**		**16.5**		**4.4**	
GHG emission for fossil fuel comparator, gCO_2/MJ	198.0	87.0	198.0	87.0	198.0	87.0
GHG emissions saving	**76%**	**54%**	**92%**	**63%**	**98%**	**96%**

% of whole chain emissions at each stage

	Using AD technology				Using other bioenergy technologies	
% of whole chain emissions	**CHP from maize silage**	**Biomethane from Maize silage**	**CHP from wet manure**	**Biomethane from wet manure**	**CHP from wood chips**	**Biomethane from wood gasification**
Crop production	60%	38%				
Harvesting and extraction	3%	2%			14%	8%
Production of silage	8%	5%			19%	11%
Transport	4%	3%	28%	11%	67%	18%
Biogas production plant	25%	16%	72%	27%		0%
TOTAL biogas production						
Upgrading		30%		52%		
Gas Injection to grid		6%		10%		64%

Highlighted values account for, in red = high proportion, in orange = medium proportion of whole chain GHG emissions

The GHG emissions savings are calculated by comparison with the reference fossil fuel comparators set out in the Renewable Energy Directive (RED). For CHP the fossil fuel comparator is EU electricity, at a GHG emissions intensity of 198 gCO_2/MJ electricity; for biomethane the fossil fuel comparator is natural gas, at a GHG emissions intensity of 87 gCO_2/MJ.

To qualify for the RHI, the biomethane needs to meet a 60% GHG emissions savings threshold, as set out in the latest amendment to the RHI (DECC 2014). This equates to emissions of less than 34.8gCO_2/MJ. Using the default values for emissions in the Ofgem Carbon Calculator (which include a conservative factor of 1.4 for the process emissions) the maize AD for biomethane system does not achieve the required GHG emissions savings. It is likely that the threshold will be met if actual site specific data are used in the model. The industry are also actively working to minimise fertiliser emissions and biomethane losses in the system, which will lead to reduced GHG emissions. However, the default values allow a like-for-like comparison across all the systems considered, and illustrate clearly that the production of maize contributes a significant quantity of GHG emissions to the overall system.

The literature suggests that in systems using a combination of feedstocks, such as maize and slurry, the performance of the digester in terms of biogas production and stability of the process will be enhanced relative to systems based on individual feedstocks (Lijo 2014).

The GHG emissions for production of biogas and biomethane can be expressed in terms of $kgCO_2eq$/tonne of maize and per ha of maize (Table 3-16).

Table 3-16 Greenhouse gas emissions for production of biogas and biomethane ($kgCO_2eq$/tonne of maize and per ha of maize).

	biogas from maize silage	**Biomethane from Maize silage**
$kgCO_2eq$/ tonne maize	56	92
$kgCO_2eq$/ha maize	3201	5269

Yield of whole crop maize, tonnes (fresh weight) /ha	57.0
GJ biomethane/tonne maize	*2.31*
GJ biogas/ tonne maize	2.32

The higher emissions from biomethane production are due to the emissions involved in upgrading the biogas. For electricity production, the model assumes no further emissions in the power production process.

Environmental impacts of the AD process and electricity and bio-methane production

This section gives an overview of the local environmental impacts of the AD production process itself and of the production of electricity or bio-methane from the biogas from the AD process. It includes impacts from the storage of feedstocks and process chemicals on site, the storage of digestate on site and the storage or discharge of waste products. Environmental impacts considered are emissions to air, water, soil, impacts on water resources, impacts on biodiversity and visual and noise impacts.Table 3-17 summarises the impacts by process activity and environmental impact, and highlights those areas of particular concern. The summary is based on work conducted for the Biomass Environmental

Assessment Tool (BEAT) by Ricardo (Defra 2008c), and on recent reviews of environmental impacts of the AD process and of biogas upgrading (Whiting 2014, Scholz 2013).

Table 3-17 Summary of environmental impacts of electricity and bio-methane production from maize feedstocks. Highlighted cells indicate that environmental impacts are: red = high impact, orange = medium impact and grey = low impact.

Activity	Impact						
	Air Quality	Water quality	Water resources	Bio-diversity	Soil quality	Visual impact	Noise impacts
Maize storage at plant	none	leakage from silage	none	none	leakage from silage	none	none
AD process	methane slippage	leaks from plant	process water requirements can be high	none	leaks from plant	low on farm, larger for centralised plant.	low
Digestate/ waste storage	methane emissions, ammonia emissions	leaks from digestate stores	none	none	leaks from storage	low on farm, larger for centralised plant.	low
Electricity production	combustion emissions	none	none	none	none	low on farm, larger for centralised plant. In particular height of chimney for dispersal of combustion emissions may be an issue.	generator noise may require shielding.
Biogas upgrading	methane emissions, H_2S emissions	process water will be discharged	some upgrading technologies require substantial water inputs	none	leaks from plant would be issue for amine systems	some technologies require high process columns	noise from compression equipment
Disposal of wastes	All digestate assumed to be spread to land. Process chemical waste will require disposal to landfill, with consequent impacts in all the above categories						

The summary shows that the most significant environmental impacts from the AD process are likely to be emissions of methane and ammonia from digestate storage, and emissions of methane during biogas production. There is lower potential for emissions of ammonia when maize is the sole feedstock for an AD plant than when combined with slurry; however, it is still a concern. Methane emissions will be lower in a well-designed and managed AD process, as the fugitive emissions in the plant will be lower and the digestion process more complete. It is of particular importance to ensure that digestate stores are covered or capped and well managed and that these controls are implemented in all AD installations to minimise methane and ammonia emissions. Leaks from the AD digester and digestate storage should be an unlikely event, but will cause considerable environmental damage if they occur.

The most significant environmental impacts of the conversion of biogas to electricity and heat via CHP are the combustion emissions and methane slippage. Combustion emissions will depend on the feedstock for the biogas and the chosen combustion technology, and equipment to manage emissions may be required. Methane slippage can be minimised by good plant design and maintenance.

The potential impacts of biogas upgrading to bio-methane will depend on the technology chosen. Table 3-18 summarises the main upgrading technologies and environmental advantages and disadvantages of each.

Table 3-18 Biogas upgrading technologies and environmental impacts

Technology	Environmental Advantages	Environmental Disadvantages
Membrane	Energy efficient (especially at low gas flow rates Low chemical/ water requirements Small footprint	Off gas contains H_2S and CH_4 and requires treatment
Liquid absorption (amine)	High CH_4 recovery	Amines are toxic and present environmental hazard in the event of leaks from the plant
Liquid absorption (water)	No chemicals required	Water use high Large footprint
Solid adsorption (Pressure Swing Adsorption)	No chemicals required	Higher CH_4 losses.

We anticipate that in the future membrane systems will become more common. This may be the case for farm crop based systems in particular, as these are likely to be smaller scale, and thus have lower biogas flow rates for which membrane technology is the most practical solution.

The environmental impacts of producing maize as an energy crop for AD is considered Section 3, but it is noted here that maize production causes significant impacts in most of the categories considered above.

3.2.2 Maize for livestock feed

Wholecrop maize has become increasingly popular as a forage for livestock in recent decades (maize area has expanded from *c.*1,000 ha in the early 1970s to around 170,000 ha in 2014 (Defra, 2014a). Forage maize is relatively easy to grow and drought tolerant and provides consistent yields of palatable forage which is of particular value to the dairy sector. From a practical point of view, the crop is largely drilled and harvested by contractors, reducing the reliance on grass silage and the associated workload for farmers. Again this can be helpful for the dairy sector where increased herd size and milk yields have put additional pressure on labour resources and management input. Finally, drilling the crop in late April / early May provides the farmer with an area onto which he can spread manure, again an issue where expansion of dairy herd size has put pressure on storage capacity.

Growing maize as an AD feedstock not only provides competition for land to grow maize but may displace the end use of the crop where the availability of suitable land is limited. In this instance, there may be an impact of maize AD through the changes in livestock diets associated with reduced availability of forage maize.

Methodology

According to IPPC 2006 guidelines (IPCC 2006, Chapter 10: Emissions from Livestock and Manure Management), methane emissions factors for enteric fermentation from livestock are calculated from the estimated intakes of gross energy (GE). The following equation (equation 10.21) is recommended for calculating emission factors for ruminant livestock:

EF= ((GE*(Ym/100)*365))/55.65

Where

EF = emission factor, kilogram CH_4 per head per year
GE = grows energy intake MJ/head/day
Ym = methane conversion factor, percent of gross energy in feed converted to methane
The factor 55.65 (MJ/kg CH_4) is the energy content of methane.

Using this equation and a number of alternative diets calculated by an animal nutritionist for this project, estimated CH_4 emission factors for each of the diets have been calculated (Table 15). The diets represent a maize-based diet and two alternatives as follows:

1. Maize-based diet – 50% maize silage and 50% grass silage on a dry matter basis
2. Grass silage + Grass silage + a by-product-based moist feed
3. Grass silage only

Results

For each diet, methane EFs (kg CH_4 /head /yr) have been estimated at two yield levels – 36kg milk which might represent a maximum average yield for a high-yielding dairy herd (11,000 litres) and 24kg which represents an industry average (7500 litres). It is important to recognise that the diets relate to feeding when cows are housed and as such this only applies for 6 months of the year for most herds.

The data (Table 3-19) demonstrate that differences between livestock diets with and without maize in terms of CH_4 EFs are likely to be small; i.e. the largest differences occurred between, a low yielding dairy herd fed on a maize-based diet (127 kg CH_4 /head /yr) compared to a grass silage + wheat based commercial feed diet (125 kg CH_4 /head /yr).

No estimates have been provided on N excretion but because diets were formulated to have similar levels of protein we would expect very little difference between diets in N excretion.

Table 3-19 Dairy cow diets for two milk yield levels (high = 36 kg milk and industry average = 24 kg milk) and associated methane emission factors (kg CH_4 /head /yr).

Diet type and yield level	**GE intake, MJ/day**	**CH_4 emission factor** (kg CH_4 /head /yr)
Maize-based -36 kg milk	418.8	164.8
Maize-based -24 kg milk	323.8	127.4
Grass silage + a by-product-based moist feed -36 kg milk	416.4	163.8
Grass silage + a by-product-based moist feed -24 kg milk	317.1	124.8
Grass silage only - 36 kg milk	420.3	165.4
Grass silage only - 24 kg milk	327.1	128.7

Summary of environmental costs and benefits of maize production

- The most significant environmental impacts from the AD process are likely to be emissions of methane and ammonia from digestate storage, and emissions of methane during biogas production.
- Methane emissions will be lower in a well-designed and managed AD process, as the fugitive emissions in the plant will be lower and the digestion process more complete.
- If some / all of the digestate cannot be spread to land (due to insufficient area available or in the case of mixed maize/ waste feedstock the digestate is unsuitable for land spreading) then the digestate will require further processing or disposal to landfill, with consequent impacts.
- Differences between livestock diets with and without maize in terms of CH_4 EFs are likely to be small.

3.3 Overall summary and conclusions

The evidence reviewed demonstrates that the magnitude of surface runoff, sediment, phosphorus (P), and nitrate (NO_3) leaching losses from maize cropped land are within the range or similar to those reported for other tillage crops.

- Surface runoff from conventional plough-based or non-inversion cultivated maize cropping are in the range of <1 mm to *c.*80 mm, these losses are similar to the range of surface runoff reported from winter cereals are within the range of *c.*1 mm to 75 mm (Defra, 2008).
- Sediment losses from conventional plough-based or non-inversion cultivated maize cropping are in the range of <0.1 to *c.*4 t ha^{-1}. In comparison, sediment losses from other tillage crops on erodible land are within the range of 0.2 to 5 t ha^{-1} (Broadman 1990; Chambers *et al.,* 1992; Evans 1993 in Chambers and Garwood, 2000; Defra, 2008). Some exceptionally high sediment losses have been reported for maize (36 t ha^{-1}, Van Dijk *et al*. (2005)), potatoes and winter cereals (of up to 180 m^3 ha^{-1}, Broadman *et al.* (2009)).
- Phosphorus losses from conventional plough-based or non-inversion cultivated maize cropping are in the range of *c.*0.3 to *c.*4.3 kg ha^{-1}. In comparison, phosphorus losses from other tillage crops on erodible land are within the range of 0.01 to *c.*4t ha^{-1} (Defra project PE0206; Chambers & Garwood, 2000).
- Nitrate leaching losses from conventional plough-based or non-inversion cultivated maize cropping are in the range of 40-*c.*80 kg NO_3-N ha^{-1}. This compares to NO_3 leaching losses from potatoes of *c.*70 kg NO_3-N ha^{-1} (Shepherd & Lord, 1996), and mean losses over a 5 year crop rotation of *c.*50 kg NO_3-N ha^{-1} (Johnson *et al*., 2002). As with all crops, it is important that soil nitrogen supply (SNS) is accounted for before applying manufactured fertiliser in order to minimise N-surplus and therefore NO_3 leaching losses.

Soil surveys have shown that late harvested crops, such as maize and potatoes, show more signs of soil degradation, due to trafficking during harvest operations, etc. when soils are wet.

- Project WQ0140, shows that surface runoff, sediment, P and NO_3 leaching losses from maize sites with good soil structure are within the range reported from other tillage crops.
- Project WQ0140 reported that ammonia losses were greater following the application of crop-based digestate (mean losses *c.*30- 50% of N applied) than following cattle slurry (*c.*15 -20% of N applied). This is consistent with the results from the DC-Agri project which concluded that

the ammonia emissions from food-based digestates (*c*.40% of total N applied) were greater than from livestock slurry (*c*.30% of total N applied). The greater NH_3 emissions from digestate is most likely due to a combination of higher ammonium N contents and elevated pH levels compared to livestock slurries.

Potential mitigation strategies for reducing the environmental impact of maize cropping involve i) cover cropping or ii) soil management techniques. A number of field studies have demonstrated that cover crops are effective at reducing runoff, sediment, P and NO_3 leaching losses. However, cover crops are only effective when well established before the on-set of over-winter drainage, furthermore there is limited evidence to suggest that post maize harvest establishment of cover crops can increase sediment losses. Overall studies have reported:

- Ryegrass oversown approximately 1 month after drilling reduced over-winter runoff by to 60% and sediment losses by up to 70% compared to the conventional treatment of bare ground (Project SP0404 & Kwaad *et al.*, 2008).
- Post-harvest established ryecorn had a minimal impact on reducing surface runoff. Furthermore, establishing ryecorn after maize harvest, more than doubled sediment losses to 1551 kg ha^{-1} compared to the conventional treatment at North Wyke (project SP0404). The project concluded that this was due to a loosening of the soil surface associated with cultivating in order to establish the cover crop.
- At the Norfolk site (Project WQ0140), oversown ryegrass, 6-months after establishment, reduced over-winter NO_3-N leaching losses by 50%, and sediment losses by 70%, compared to the conventional treatment of bare ground. This finding is consistent with previous research, which has demonstrated that cover-crops are most effective at reducing NO_3-N leaching when drilled by late August to early-September (Davies *et al*., 1996; Shepherd and Lord 1996). At the Devon site oversown ryegrass, 6-months after establishment reduced over-winter runoff by 40% (although these results could not be confirmed statistically), and sediment losses by 80%, compared to the conventional treatment of bare ground.

Maize is vulnerable to competition at the early growth stages and it is important that any method to establish cover-crops does not impact on maize yield or quality.

- Project SP0404 showed that, establishing white clover at maize drilling, significantly reduced maize yields in both harvest years 1999 and 2000, with mean reductions of *c*.50% and 40%, respectively.
- There is limited evidence from the UK available on the impacts of oversowing on maize yields. However, the results from SP0404 indicate that any reductions are not significant (i.e. *c*.4%).
- WQ0140 demonstrated that it is not practical to retain the ground cover in the following spring and establish a maize crop by strip-tilling into a growing ground cover, because of yield reductions of up to 90% compared with conventional maize production.

In summary, oversowing maize is one technique which can establish a cover crop that is effective at reducing surface runoff, sediment, P and NO_3 leaching losses. However, it is important that management strategies for oversowing maize grown in the UK are implemented, which ensure: 1) that the cover crop germinates before the maize canopy closes, otherwise it will not establish due to shading, 2) that the cover crop does not compete with the maize crop at the early stages of development, which could result in a reduction in crop yield and 3) in continuous maize rotations any cover crops should be managed to ensure there is no detrimental impact on subsequent maize yields.

Herbicide use controls weeds and can reduce the food and habitat resources for higher trophic levels (e.g. bees, farmland birds and insects). Firbank *et al.* (2003) reported that compared to oilseed rape and sugar beet, maize had the lowest biodiversity for both flora and fauna. Project WQ0140, has demonstrated that strip tillage with ground cover (ryegrass or biodiverse seed mix) in maize crop systems can help improve above and below-ground invertebrate biodiversity, whilst bumblebee biodiversity also increased with strip-tillage-biodiverse seed mix. However, strip tillage into ground cover was not economically viable as maize yields were reduced by between *c.*50-90percent compared to conventional practice.

Studies investigating the effectiveness of soil management strategies to mitigate the environmental impact of maize cropping have reported:

- Overall, neither non-inversion nor strip-tillage cultivation, demonstrated any significant impacts in reducing diffuse water pollution.
- When soil conditions are appropriate, chisel ploughing post maize harvest can be effective at reducing surface runoff and sediment losses. However, there is a risk that soil conditions post maize harvest may not be suitable for cultivation, especially if crops are harvested late (i.e. October/November) and soils are wet.

The assessment of the potential environmental impacts (costs) and benefits of maize production for use as i) a feedstock for bioenergy production and ii) livestock feed found that:

- The most significant environmental impacts from the AD process are likely to be emissions of methane and ammonia from digestate storage, and emissions of methane during biogas production.
- Methane emissions will be lower in a well-designed and managed AD process, as the fugitive emissions in the plant will be lower and the digestion process more complete.
- Differences between livestock diets with and without maize in terms of CH_4 EFs are likely to be small.

Recommendations for further work

The evidence reviewed has demonstrated that oversowing maize with ryegrass can be effective at reducing over-winter diffuse pollution. However, before this mitigation strategy can be effectively implemented, further research is required to develop:

1. Oversowing methods *(e.g. broadcasting versus drilling and effect of cover crop species)*, to improve the success rate of establishing ground cover that is effective at reducing diffuse water pollution without reducing maize yields or quality.
2. Cover crop destruction techniques to ensure no negative impacts on subsequent crop yields or quality.
3. Disseminate findings to farmers to ensure uptake of best available practices

Ammonia emissions following land applications are higher from digestate than from livestock slurry. Further information is required to develop innovative management strategies to reduce N losses (e.g. acidification, separation of solid and liquid fractions) and maximise N (and P) nutrient use efficiencies (NUE) of the range of digestates from the anaerobic digestion of different feedstocks (food, manure and crop-based). This information is crucial to support improved advice to farmers on how to maximise NUE and to minimise agriculture’s environmental footprint, and the development of sustainable intensification of agricultural systems and closed-loop nutrient systems.

4 Crops displaced by maize and resulting environmental impact

4.1 Crops displaced by maize being grown for anaerobic digestion

An analysis of the June Agricultural Survey data was used to identify which farm activities are being displaced by maize being grown for anaerobic digestion. The intention was that crop displacement would be identified for farms, with stratification by robust farm type, farm size and whether the farm has on-farm anaerobic digestion plant.

4.1.1 Methodology

Data, for England only, from the June Agricultural Survey from 2010 and 2013 was used for the analysis. The data provided were at holding level, with the areas of crops grown, robust farm type and numbers of livestock on each holding. In addition, response data from farms that were growing maize in 2014 were provided from the 2014 June Agricultural Survey. This response data included a breakdown of the area of maize being grown for different purposes (grain, forage or anaerobic digestion).

To ensure that the analysis of the data was robust, only data that were actual responses were used in the analysis, this led to a total of 102,836 holdings within the datasets for which actual response data was available for at least one of the survey years. Using the information from the 2014 survey on the production of maize, we were able to classify farms into three categories:

- Farms growing maize for anaerobic digestion,
- Farms growing maize for fodder or grain, and
- Farms not growing maize.

For the first two categories, the data was then analysed to determine a sample year and a baseline year for analysis. The criteria for selection of baseline and sample year were that, for a given farm, both years had to have actual response data and that there had to be an increase in maize production between the two years. The ideal situation was to have 2010 as the baseline year (as it was assumed that no farms would have been growing maize for anaerobic digestion in 2010) and 2014 as the sample year, however if this was not possible, then the following combinations were tested 9in order of preference):

- A baseline year of 2010 and a sample year of 2013, and
- A baseline year of 2013 and a sample year of 2014.

This reduced the dataset to a total of 2337 holdings, of which 207 were growing maize for anaerobic digestion. The breakdown of these holdings by robust farm type for farms growing maize for anaerobic digestions and those farms growing maize for other purposes are shown in Table 4-1 and Table 4-2.

The spatial location of the holdings growing maize for AD are shown in Table 4-1 with a breakdown of the number of farms growing maize for AD in each government office region shown in Table 4-2. From this examination it was clear that there was insufficient data to provide a full regional breakdown of the displacement of crops by maize for anaerobic digestion. For those regions where sufficient data was felt to be available (East England and East Midlands), there was only sufficient data for cropping farms.

Table 4-1 Breakdown of farms used in the analysis that were growing maize for AD by Robust Farm Type.

Robust Farm Type	Number of Farms
Mixed	20
Cereals	48
Dairy	18
General Cropping	98
Horticulture	6
Specialist Pigs And Poultry	7
LFA & Lowland Grazing Livestock	10
Total	**207**

Table 4-2 Breakdown by Robust Farm Type of number of farms used in the analysis that were growing maize for fodder or other purposes.

Robust Farm Type	Number of Farms
Mixed and other	383
Cereals	199
Specialist pig	17
Lowland grazing livestock	463
Dairy	894
General cropping	112
Horticulture	20
Specialist poultry	20
LFA Grazing Livestock	22
Total	**2130**

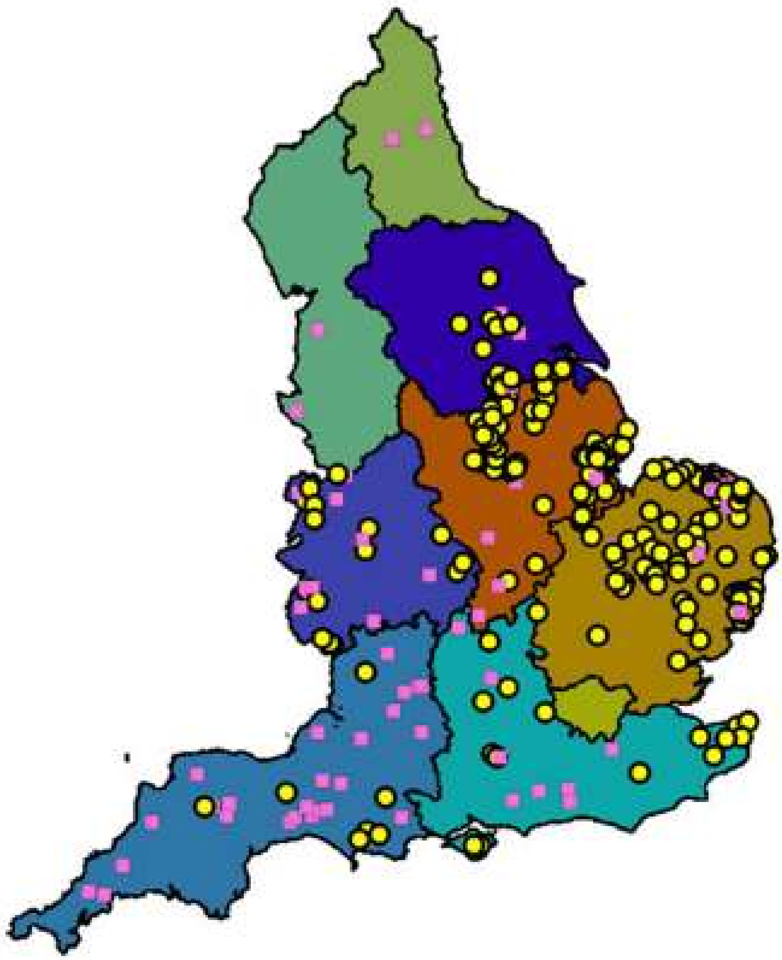


Figure 4-1 Approximate location of all farms identified as growing maize for anaerobic digestion in 2014 June Survey responses (pink squares are livestock farms and yellow circles are arable farms).

Table 4-3 Breakdown of farms used in analysis of farms growing maize for AD, by GOR and farm type (disclosive data have been removed).

Government Office Region	**Crops**	**Livestock**	**Total**
East	60	9	**69**
East Midlands	44	*	**44**
London	*	*	*****
North East	*	*	*****
North West	*	*	*****
South East	11	7	**18**
South West	6	21	**27**
West Midlands	12	6	**18**
Yorks & The Humber	19	*	**19**
Total	152	43	195

A method was established that provided a weighting for each crop category in the June Agricultural Survey that reflected how likely a hectare of that crop would be to be replaced by a hectare of maize. To do this, the method follows the following steps:

- For each farm:
    - identify the additional area of maize in 2014 beyond that expected (based on proportion of total area grown as maize in 2010)
    - For each crop other than maize:
        - If 2014 area is less than expected:
            - Calculate the crop area that is likely to have been displaced by maize, accounting for changes in area of other crops
- Create the average displacement for each crop, weighted by change in maize area and normalize by total displacement of all crops
- Create the average area baseline for each crop, weighted by change in maize area and normalize by total area of all crops
- Create individual crop weightings by dividing the relative displacement by the relative baseline for each crop.

A weighting value of 1 indicates that a crop is no more or less likely to be replaced by maize. A value of less than 1 indicates a crop is less likely to be displaced by maize, and a value above 1 indicates a crop is preferentially being displaced by maize. To provide some confidence on the weightings, a bootstrapping method was used to randomly sample the data 100000 times, producing a mean weight for each crop as well as lower and upper confidence intervals. If the mean and both the upper and lower confidence intervals were either all smaller than 1 or all greater than 1 then the result was considered to be robust.

4.1.2 Weighting by crop group and region

The weightings for each crop by grouping are shown in Table 4-4.

On the Livestock farms that aren't growing maize for anaerobic digestion, we can see that maize is more likely to displace a large number of crops: winter barley, spring barley, oats, triticale, forage, root crops, winter oilseeds, beans, potatoes and fallow. This is not surprising as the displaced crops are all alternative fodder crops to maize or low value crops. It is also not surprising that on livestock farms not growing maize for AD that grassland is less likely to be displaced

For the arable farms not growing maize for anaerobic digestion we can see that winter wheat and permanent grassland are less likely to be displaced. Forage root crops, beets, temporary grass and fallow are more likely to be displaced. This again probably reflects the relative value of these two crops with respect to maize and also the main rotations within arable cropping systems.

For the farms that are growing maize for anaerobic digestion (and the majority of these are growing all of their maize for anaerobic digestion), it can be seen that there are few robust results, meaning that maize is likely to displace crops in relation to their contribution to the total area of the farm. For the livestock farms it can be seen that spring barley and triticale are more likely to be replaced than other crops and permanent grass is highly unlikely to be displaced, as it will be needed for grazing. For the arable farms growing maize for anaerobic digestion, it is less likely that winter wheat, a high value crop in arable systems, will be displaced by maize, and there is a preference to replace both spring barley and non-rotational grassland with maize crops.

Table 4-4 Robust weightings for each crop broken down by growing maize for AD or for other reason (JAC 2014) and by farm type. Non robust weightings have been omitted for clarity

	Maize for AD			Maize not for AD		
	All	Crops	Live stock	All	Crops	Live stock
Number of Farms	**207**	**152**	**55**	**2130**	**332**	**1798**
Wheat	0.54	0.52	-	0.72	0.39	-
Winter Barley	-	-	-	1.97	-	2.00
Spring Barley	3.16	3.25	2.61	-	-	1.92
Oats	-	-	-	2.21	-	2.33
Mixed Grain	-	-	-	-	-	-
Rye	-	-	-	-	-	-
Triticale	11.51	-	3.83	5.50	-	6.69
Other Forage	-	-	-	2.71	-	-
Roots, Beets, Brassicas (forage)	-	-	-	4.86	6.23	4.62
Maize	-	-	-	-	-	-
Winter OSR	-	-	-	-	-	2.09
Spring OSR	-	-	-	-	-	-
Beans	-	-	-	2.85	-	3.02
Peas	-	-	-	-	-	-
Potatoes	-	-	-	-	-	2.21
Beets	-	-	-	-	2.68	-
Temporary Grass	-	-	-	-	2.23	-
Permanent Grass	-	1.96	0.45	0.54	0.55	0.55
Rough Grazing	-	-	-	-	-	-
Fallow	-	-	-	4.31	3.32	5.35

The results for the East of England and East Midlands cropping farms are shown in Table 4-5.

It is clear that there are regional differences, with the East of England showing no preference for displacement of crops by maize for AD, apart from a strong aversion to replacing wheat by maize for AD. In the East Midlands, those farms growing maize for AD show a strong preference for displacing beans by maize for AD, but a distinct aversion to displacing wheat by maize for anaerobic digestion. In contrast to the analysis of the data for the whole dataset, for those farms not growing maize for AD in both regions show as strong preference for replacing temporary grassland.

Table 4-5 Robust weightings for each crop for cropping farms growing maize for AD or for other purposes in East England and East Midlands (non-robust weightings omitted for clarity).

	East England		East Midlands	
	Maize for AD	*Maize not for AD*	*Maize for AD*	*Maize not for AD*
Number of Farms	60	50	44	51
Wheat	-	0.38	0.28	0.39
Winter Barley	-	-	-	-
Spring Barley	-	-	-	-
Oats	-	-	-	-
Mixed Grain	-	-	-	-
Rye	-	-	-	-
Triticale	-	-	-	-
Other Forage	-	-	-	-
Roots, Beets, Brassicas (forage)	-	-	-	-
Maize	-	-	-	-
Winter OSR	-	-	-	-
Spring OSR	-	-	-	-
Beans	-	-	8.68	-
Peas	-	-	-	-
Potatoes	-	-	-	-
Beets	-	-	-	-
Temporary Grass	-	7.90	-	3.71
Permanent Grass	-	-	-	-
Rough Grazing	-	-	-	-
Fallow	-	6.41	-	-

4.1.3 Evidence of preferential displacement

The analysis suggests that there is limited preferential displacement of crops by maize being grown for anaerobic digestion. This may be unexpected, but is perhaps not surprising when we consider that the net margin for maize production for anaerobic digestion is higher than other crops (Vogel, Hellawel & Collins, 2011). Hence, in economic terms it does not matter which crop is displaced. However, due to the small sample size, the results must be treated with appropriate caution. We are confident that the analysis approach used is robust since it provides weightings that make logical sense for displacement of crops by maize where it is not being grown for anaerobic digestion, where the sample size is much larger.

For the assessment of environmental impacts, the analysis suggests that there is potential for any crop to be displaced and therefore the net impact needs to be determined for all crops included in the June Census. Spatially differentiated assessment of the environmental impacts will require some assumptions to allow downscaling of national scale impacts. The low sample size for farms growing maize for anaerobic digestion at Government Office Region (GOR) level means that we have to assume that the national scale crop displacement profile is applicable at regional and sub-regional scales, although we can use the response data to determine the proportion of farms in each GOR growing maize for anaerobic digestion. It will also have to be assumed that farms are classified as either cropping or livestock since the sample size is too small to allow differentiation by robust farm type.

4.2 Identifying the main indirect impacts of maize production

Data were used from the analysis of Defra June Survey data along with the changes in area of different crop types. The analysis focused on those farms that were known to be growing maize from the June Survey response for 2014. Holdings were selected as described in section 2.4.1 above.

The results showed the change in total area for each crop type broken down by whether the farm was crop or livestock focussed and also whether in 2014 it was growing maize for AD or not.

Weightings were provided for each crop type for those farms growing maize for AD, broken down by region. The weightings show the likelihood that a crop is displaced and provides a relative ranking of the crop types. However, for most regions there was not sufficient data to allow the weights to be calculated, and the analysis showed no clear preferences for crop type displacement at a national scale. Therefore, in the assessment of likely impacts of displacement of other crops to other locations, we have chosen to study crops based on the decrease in area as a proportion of the increase in area of maize grown for AD. On this basis Figure 4-2 shows the top three crops displaced by maize grown for AD, for crop and livestock farms.

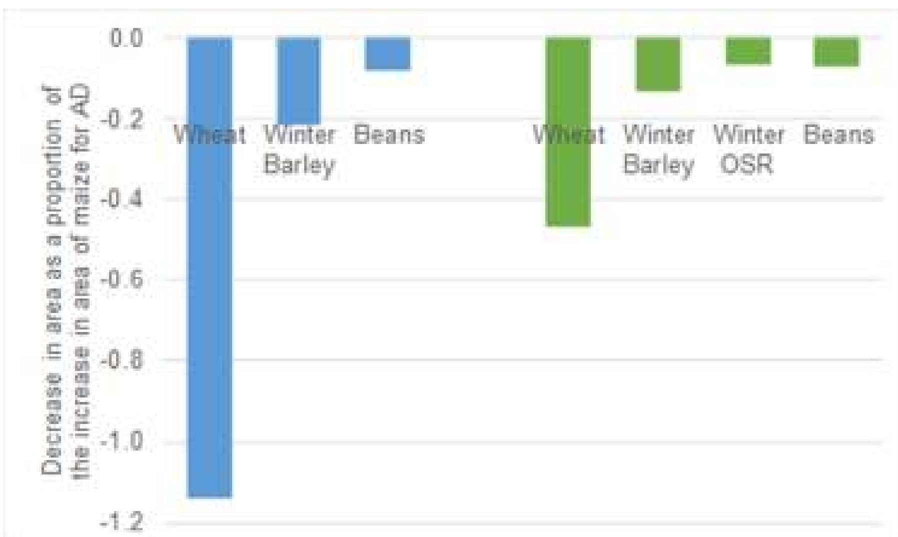


Figure 4-2 Decrease in area of crops as a proportion of the increase in area of maize for AD, for crop-focussed and livestock-focused farms.

Displacement of crop production by other crops for a different end use results in a complex chain of consequences that is highly uncertain. The first-displaced crop (e.g. displacement of wheat when maize for bioenergy is introduced into a farm rotation, and less wheat is grown in the same rotation) probably results in more wheat being grown in another place, probably displacing another crop, and this displacement may continue making a chain of displaced crops that can end with land use change (LUC) when more land is brought into agriculture in another place. When considering the impacts of the introduced crop (in this case maize for bioenergy), the end of chain LUC is known as indirect land use change (ILUC).

However, ILUC is not a certain consequence of new crop production for bioenergy, as other possibilities include change in productivity (more competition for land may push up prices of agricultural products and increase productivity through greater investment and innovation), and production on agricultural land that would otherwise be uncropped. The actual consequences depend on market demands for agricultural products and for land, as well as the policy environment.

The consequences of crop displacement cannot be determined, but there are several methods that can be used for estimation of GHG emissions from ILUC. These include complex modelling approaches, scenario-based estimates, and top-down allocation of total global LUC GHG emissions to activities that use land.

The objective was to describe a range of likely impacts of displacement of other crops to other locations, with the emphasis on global warming potential, and comment on other possible impacts. This qualitative assessment supplements the data provided by ADAS (see above) on the crops displaced by the expanding production of maize for bioenergy

4.2.1 Methods

Based on the data provided by ADAS (see Figure 4-2 above), the following crops were selected, these having large decreases in area as a proportion of the increase in area of maize for AD.

- Wheat
- Winter barley
- Winter oilseed rape
- Beans

Displacement of grass was not considered because usually, either the displaced grass does not result in ILUC because the grass forage is directly replaced by maize production for animal feed (silage), or the grass area falls because of falling livestock numbers. This recognises that other changes occur alongside the change in crop production to grow maize for AD. The occurrence of other changes alongside the change in crop production to grow maize for AD is also evident from the decrease in area of wheat being larger than the increase in area of maize.

For each crop it was assumed that displacement by maize resulted in zero production, where there had previously been production at UK average yields. It was assumed that this production was made up in another place, and that GHG emissions from ILUC occurred.

For wheat, barley and oilseed rape, to estimate indirect GHG emissions from ILUC, European Commission ILUC factors were used, together with data for average yields, biofuel yield per tonne of feedstock, and energy content of the fuels. As beans are not grown for biofuel, we have provided an estimate from literature for displacement, assuming that lost production was made up by production of soya beans in South America. We used a CO_2e value from Weightman *et al.,* 2010.

4.2.2 Estimates of indirect land use change GHG emissions

Table 4-6 provides estimates of ILUC GHG emissions for the displacement of wheat, barley and oilseed rape. Yield data were from Defra (2014); biofuel yield and energy content data were from Department of Transport (2012); and ILUC emissions data per MJ were from European Commission (2012).

To provide an upper estimate of ILUC GHG emissions, we used displacement of beans by maize, with an assumed consequence of importing soya from Brazil to supply animal feed that would have been supplied by beans. This is a simplistic assumption designed to give a maximum estimate of consequential (indirect), emissions.

Table 4-6 Estimated ILUC emissions (tCO_2e/ha) for wheat, barley and oilseed rape, with supporting data

Crop	Yield (t/ha)	Biofuel yield (L/t)	Energy content of biofuel (MJ/L)	Estimated ILUC emissions (gCO_2e/MJ)	Estimated ILUC emissions ($kgCO_2e/t$)	Estimated ILUC emissions (tCO_2e/ha)
Wheat	8.6	367	21	12	92.5	0.80
Barley	6.4	367	21	12	92.5	0.59
Oilseed Rape	3.6	429	33	55	778.6	2.80

We used a UK yield for beans of 4.20 t/ha (Defra, 2014b), a yield of soya in Brazil of 2.85 t/ha (FAOStat, 2015) and a value of 4.62 t CO_2e/t soya beans imported into the EU from South America (Weightman *et al.,* 2010). This upper estimate of GHG emissions was 19.4 t $CO_2e/ha/year$.

Overall, we have estimated a range of 0.59 to 19.4 t $CO_2e/ha/year$, depending on the crop displaced by maize. These are additional emissions to any emissions (or removals) from the direct LUC (i.e. the balance of emissions from production of maize and avoided emissions from not producing the displaced crop). Using data from Defra project FO0404 (Wiltshire *et al.,* 2009), we have estimated the direct LUC emissions to be -2.6 t $CO_2e/ha/year$. This is based on emissions from growing winter feed wheat, of 4.6 t $CO_2e/ha/year$, at a yield of 8.3 t/ha, and emissions from production of maize silage, of 2 t $CO_2e/ha/year$, at a yield of 11 t/ha.

As the actual displacement of crops by maize for AD will include a range of crops, with potentially high-impact crops contributing a small percentage of the total area displaced, probably around 10%. If we take an example of an arable rotation in which maize displaces wheat, barley, oilseed rape and beans in the approximate proportions indicated by the analysis of Defra June Census data, and we use our upper ILUC emissions estimate for beans, we estimate that the indirect emissions would be 3.1 t $CO_2e/ha/year$. If we use a lower estimate for beans, by assuming a similar value to that for oilseed rape, the indirect emissions would be 1.1 t $CO_2e/ha/year$.

Uncertainties in these estimates are very high and related to the uncertain chain of consequences following crop displacement, with complex interactions between effects on crop product prices and market demand for crop products. This analysis provides indicative values to show the likely scale of the indirect emissions.

4.2.3 Non-GHG impacts of displacement of other crops to other locations

Environmental impacts of biofuel production have been widely discussed internationally and the indirect impacts of growing maize for bioenergy are similar in principle to environmental impacts of crop displacement for any new use of land.

The main impacts, in addition to global warming potential, relate to soil degradation, effects on water resources, and loss of biodiversity.

A study in Germany by Gutzler *et al*., (2015) examined the direct impacts of a 20% increase in silage maize cultivation for biogas production (compared to a business as usual scenario). This increase led to increased soil erosion risk and a loss of biodiversity. With regards to biodiversity, the habitat area available to Corn Buntings and Skylarks was reduced by 28.2% and 21.3% respectively due to a lack of suitable breeding areas if maize cultivation was increased by 20% (Gutzler *et al.,* 2015). There is evidence in the literature of direct impacts of maize production for bioenergy. However, whilst papers are available that discuss the methodologies available or merits of consequential life cycle assessment (Sanchez *et al*., 2012; Marvuglia *et al*., 2013), the indirect impacts are less readily available.

Vazquez-Rowe et al., (2014) conducted a study in Luxembourg to examine the consequential impacts of increasing maize cultivation for energy production. In this scenario, no new land was brought into cultivation; however, the study revealed that negative environmental impacts arise due to new import/export flows of maize or other crops from neighbouring countries. If additional land is required to grow food crops in neighbouring regions or countries for export, this will have consequences in terms of land use change.

As for global warming potential, the non-GHG impacts are highly uncertain, and affected by market forces. Despite the uncertainty, it is a reasonable assumption that any new use of land that displaces food production will lead to some degree of ILUC and conversion of non-agricultural land to agricultural land will have environmental impacts.

4.3 Environmental Impacts of crop displacement by maize grown for AD in England

The aim of this analysis was to calculate the environmental impact of changes in cropping due to increase production of maize for anaerobic digestion (AD).

The work consisted of two mains stages:

1. *Calculation of the displacement of crops by maize grown for anaerobic digestion under scenarios of percentage increases in maize area.*

   The aim of this stage of the work was to develop a methodology for calculation of the area of different crops displaced by increased production of maize for anaerobic digestions. This was based on the weightings that were calculated from the analysis of June census data in work package 2.1.2 and task 1 of work package 2.3 (section 5). These weightings specified how likely a crop was to be replaced by maize on a hectare by hectare basis, based on trends in cropping from the June Agricultural Survey (JAS) data. Where maize for anaerobic digestion was not already being grown in a catchment a methodology was developed to determine the displacement as it is not possible to apply a simple percentage increase to the maize area in these catchments.

2. *Quantification of the net environmental impacts*

   The aim of this stage of the work was to use the FarmScoper and EAgRET tools to calculate the net change across a range of environmental impacts metrics of displacing one hectare of each crop category in the JAC by one hectare of maize. The total environmental impact within a given geographical region could then be calculated by creating a weighted some of the net impacts.

Due to the limited data that was available for the calculation of crop displacement by increased production of maize for anaerobic digestion, and the small number of farms currently producing maize for anaerobic digestion, it was not possible to calculate crop displacement at Water Framework Directive waterbody level. Therefore all crop displacement figures were calculated on a Water Framework Directive Management Catchment (WMC) scale, of which there are 89 in England Figure 4-3 shows the amount of maize grown in 2014 specifically for AD by WMC. The total area of WMCs growing maize for AD is 106154 Km^2 and the total area of the WMCs not growing maize for AD is 30250 Km^2. According to the JAS data from 2014, there were 42 WMCs where there was no current production of maize for AD.

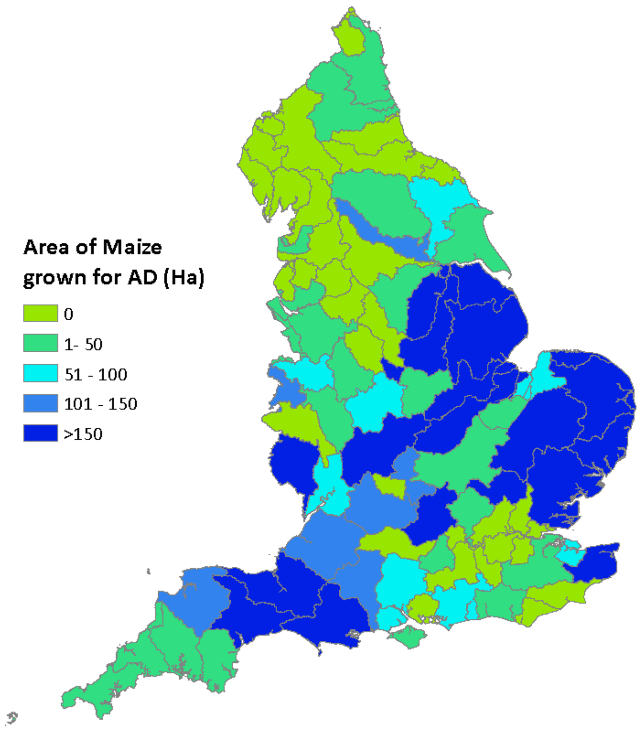


Figure 4-3 The area of maize grown specifically for AD by WMC (from the 2014 June Agricultural Survey)

4.3.1 Methodology

Calculation of crop areas displaced by maize for AD

Four different scenarios were considered, with a 25%, 50%, 100% and 200% increase in the area of maize grown for AD respectively. Total areas of each of the crop categories in the June Agricultural Survey were calculated, broken down by the 88 WMCs in England. For WMCs already growing maize specifically for AD, the increase in maize area was calculated by multiplying the area of maize grown by the respective proportional increase for each scenario. The amount of this additional area lost from each crop type was then calculated by multiplying the additional area of maize by the weighting calculated previously. Non-robust weightings were assumed to have a value of 1, meaning that a crop was no more or less likely to be displaced by maize than any other. The weightings were then normalised so that they summed to 1, allowing them to be used as a simple multiplier on the total extra area of maize, apportioning the displacement to each of the other crops being grown. This was done separately for cropping and livestock farms using the weightings calculated specifically for each farm type. It was decided that rough grazing was very unlikely to be displaced by maize, as by its nature it is usually unsuitable for any uses other than grazing. Therefore its weighting was set to zero in the methodology described above to ensure that no rough grazing was displaced by maize.

For WMCs not currently growing maize specifically for AD (cropping and livestock), a slightly different approach was taken. For each WMC growing maize for AD, the increase in area of maize (total area of crop displacement) was calculated as a proportion of the total crop area in that WMC. An average was taken of this proportion for each of the 4 scenarios. This average proportion was then applied to the total crop area of each of the WMCs with no maize for AD, to estimate the potential expected displacement if maize was to start being produced for AD in each of the four scenarios. The steps described above were then followed to attribute the displacement to each of the crop categories, using the weightings calculated previously.

As many of the WMCs currently not growing maize for AD may have a good reason for not doing so (i.e. climate), it was decided to report the changes in area and subsequent emissions separately for WMCs initially growing maize for AD and those not. This was because the results for WMCs not growing maize for AD are not necessarily as robust due to the assumptions have had to have been made. WMCs not already growing maize for AD tend to have a larger proportion of their area made up of grassland and rough grazing than the WMCs that are already growing maize for AD, which can possibly result in a significant area of grass being displaced by maize using the method described above. As grassland has a low environmental impact, this can result in perceived large environmental impacts of its displacement by maize. In reality, it is unlikely that permanent grassland will be displaced by maize. Despite this assumption, it is worth noting that there may be other reasons for WMCs not producing maize for AD, such as them being predominately urban or not having an AD plant within a feasible distance.

Table 4-7 and Table 4-8 show the national displacement of each crop under each of the four scenarios, for WMCs growing maize for AD and WMCs not growing maize for AD respectively.

Calculation of Environmental Impacts of Displacement by Maize

The environmental impact of moving from a hectare of each of the crop categories to a hectare of maize was calculated using Farmscoper and EAgRET. Farmscoper produces environmental impacts for each WMC, rainfall zone and soil type and so a weighted impact was calculated for each WMC according to the proportion of each WMC falling under each of the rainfall zones and soil type categories. EAgRET produces a national average impact for each metric. A summary of the environmental impacts of moving from growing one hectare of each crop to one hectare of maize are shown in Table 4-9 and Table 4-10, from FarmScoper (averaged across all WMCs) and EAgRET respectively. The change in crop area in hectares was then multiplied by this impact to provide a total impact for each WMC and for each of the four scenarios. The emissions were then summed to come up with a national impact for each of the 4 scenarios of increased maize production. Note that for calculation of the net change in emissions, manures were not included as it was assumed that the same amount of manure would still be being applied to the land and hence there would be no net change in emissions from manure applications to land.

The WMCs where maize for AD was already being grown were considered as separate scenarios to those where maize for AD was not currently being grown. Therefore the results provide both the impacts of increasing the area of existing maize for AD as well as the impacts of starting to produce maize for AD where it has not been produced to date.

Table 4-7 Area of each crop type (ha) displaced (only on WMCs initially growing Maize for AD) by Maize for AD in each of the four scenarios.

Crop	25%	50%	100%	200%
Beans	65	131	318	523
Beets	119	238	584	951
Fallow	75	151	373	604
Mixed Grain	1	2	4	6
Oats	36	73	183	292
Other Forage	7	13	33	53
Peas	20	39	95	156
Permanent Grass	576	1152	1541	4608
Potatoes	74	148	364	591
Roots, Beets, Brassicas for Forage	8	15	39	62
Rye	10	19	47	76
Spring Barley	470	939	754	3758
Spring OSR	6	11	28	45
Temporary Grass	171	342	866	1369
Triticale	7	14	45	56
Wheat	590	1181	3148	4724
Winter Barley	164	328	815	1310
Winter OSR	399	797	1949	3189
Total Displacement	**2797**	**5594**	**11187**	**22374**

Table 4-8 Area of each crop type (ha) displaced (only on WMCs not initially growing Maize for AD) by Maize for AD in each of the four scenarios.

Crop	25%	50%	100%	200%
Beans	6	13	34	52
Beets	0	1	3	4
Fallow	12	23	62	92
Mixed Grain	1	1	3	5
Oats	16	32	86	127
Other Forage	4	8	21	31
Peas	3	5	13	20
Permanent Grass	678	1356	2266	5436
Potatoes	5	11	29	42
Roots, Beets, Brassicas for Forage	4	8	21	30
Rye	1	1	3	5
Spring Barley	139	277	292	1112
Spring OSR	1	2	5	7
Temporary Grass	199	398	1130	1593
Triticale	7	14	60	58
Wheat	110	219	603	879
Winter Barley	47	94	258	378
Winter OSR	37	74	196	297
Total Displacement	1268	2537	5085	10168

Table 4-9 Impacts of moving from growing 1 hectare of each crop to 1 hectare of maize. From Farmscoper.

Crop displaced	Nitrate-N (kg)	Phosphorus (kg)	Sediment (kg)	Ammonia (kg)	Nitrous Oxide (kg)	Soil Carbon (t CO_2)	Energy Use (kg CO_2)
Beans	-14.5	0.2	60.9	5.1	1	5.6	1200.5
Oats	1.4	0.2	124	-3.1	-0.1	0	1200.5
Other Forage	10.7	0.1	37.5	2.9	0.6	0	1176.7
Peas	-14.6	0.1	12.8	5.1	1.1	5.6	1200.5
Permanent Grass	24.3	0.9	783.9	3.5	2.3	-10	134.9
Potatoes	-41.1	0	68.5	-4.9	-1.9	0	-1067.8
Roots, Beets and Brassicas for Forage	-0.4	0	43.2	1.3	-1.7	0	1200.5
Rough Grazing	25.8	1.2	885.8	5.1	3.3	-8	1458.7
Rye	0.8	0.2	124	-3.4	-0.1	0	1200.5
Spring Barley	0	0	-15.2	-3.9	-0.3	0	1004.8
Sugar Beet	-5.4	0.3	199.6	-3.1	-2.2	-7.7	984.2
Temporary Grass	20.3	0.9	783.9	1.5	1.3	-10	1254.4
Triticale	0.8	0.2	124	-3.4	0	0	1200.5
Wheat	-2.4	0.2	123.6	-10.7	-2.4	0	819.9
Winter Barley	-1	0.1	123.6	-6.9	-1	0	1011.2
Winter OSR	-18.6	0.8	646.8	-11.2	-2	-7.7	1084

Table 4-10 Impacts of moving from growing 1 hectare of each crop to 1 hectare of maize. From EAgRET.

Crop displaced	Carbon Dioxide (kg)	Nitrous Oxide (kg)	GWP (kg CO_2e)	Energy Use (GJ)	Acidification (kg SO_4e)	Eutrophication (kg PO_4e)	Nitrogen Balance (kg)
Beans	701.6	1	991.4	4.4	56.6	10.9	-106.3
Oats	24.6	-2.6	-764.7	0	-120.6	-22.8	-82.2
Other Forage	603.8	-1	312.7	3.7	32.5	6.3	-4.9
Peas	740.6	1	1034.9	4.5	56.5	10.9	-119.2
Permanent Grass	975	0.9	1238.8	11.9	19.1	3	150.4
Potatoes	1709.2	-1.7	-2210.9	-13	-53.7	-11.1	-110.6
Roots, Beets and Brassicas for Forage	-29.7	-0.9	-311.2	2.1	-12.1	-3	-63.3
Rough Grazing	1299.2	2	1907.4	13.7	63.6	11.4	109.8
Rye	-189.6	-0.8	-420.1	-1.8	-35.9	-6.7	-41.9
Spring Barley	-62.9	-1	-359.2	-0.6	-41.6	-7.8	-57.8
Sugar Beet	-623.1	-5.5	-2251.7	-6.4	-32.9	-6.7	-95.9
Temporary Grass	429.5	-0.3	339.7	8.6	-34	-7.1	-184.6
Triticale	-264	-0.7	-458.6	-2.7	-35.9	-6.8	-65.6
Wheat	-1090.8	-3	-1998.4	-8	-115.7	-21.9	-48.7
Winter Barley	-305.1	-1.9	-857.1	-1.9	-74	-14	-54.3
Winter OSR	-558.3	-3	-1453.6	-2.6	-120.2	-22.5	-152.2

Table 4 10 (continued) Impacts of moving from growing 1 hectare of each crop to 1 hectare of maize. From EAgRET.

Crop displaced	Phosphorus Balance (kg)	Abiotic Resource Use (kg Sbe)	Nitrogen Fertiliser (kg)	Eutrophication (kg PO_4)	Phosphorus Fertiliser (kg)
Beans	-19	2.1	60	10.9	19
Oats	3	-0.2	-32	-22.8	8
Other Forage	6.8	1.6	34	6.3	22
Peas	-26.8	2.2	60	10.9	19.5
Permanent Grass	-45	4.6	12	3	22
Potatoes	-95.1	-2.2	-57.5	-11.1	-57.1
Roots, Beets and Brassicas for Forage	-35	1.6	-17.4	-3	-1.7
Rough Grazing	-37.1	5.8	60	11.4	30
Rye	11.3	-0.2	-40	-6.7	16
Spring Barley	-9	-0.5	-46	-7.8	8
Sugar Beet	-18.7	-0.5	-36	-6.7	9
Temporary Grass	-50	3	-45	-7.1	17
Triticale	0.7	-0.2	-40	-6.8	16
Wheat	12.7	-2.4	-126	-21.9	4
Winter Barley	-5.4	-1.3	-81	-14	2
Winter OSR	-22.6	-2.4	-131	-22.5	5

4.3.2 Estimates of GHG emissions due to expansion of maize in WMCs

Note: The FarmScoper and EAgRET results assume digestate is not recycled to land. Recycling the digestate will reduce P-requirements and is likely to increase NH_3-emissions from application relative to baseline scenarios, impacts on NO_3-N leaching will depend upon application timing.

Farmscoper Results

Table 4-11 and Table 4-12 show the change in emissions predicted from the FarmScoper runs for each of the four scenarios, for WMCs currently growing maize for AD and those not doing so, respectively. The change in emissions for each scenario scale linearly with the magnitude of increase in crop area displaced (Table 4-11 and Table 4-12) as expected and hence these results can be expressed in kilograms per hectare displace to allow direct comparison between the 'Maize for AD' and 'No Maize for AD' scenarios (Table 4-13).

Table 4-11 Farmscoper results for each scenario, for WMCs already growing maize for AD

Pollutant	25% increase	50% increase	100% increase	200% increase
Nitrate-N (t)	6.6	13.21	26.41	52.82
Phosphorus (t)	0.45	0.9	1.81	3.61
Sediment (t)	337.73	675.46	1350.91	2701.82
Ammonia (t)	-12.01	-24.01	-48.03	-95.06
Nitrous Oxide (t)	-1.23	-2.46	-4.93	-9.86
Soil Carbon (000s t)	-11.03	-22.05	-44.1	-72.27
Energy Use (t CO_2)	2769.77	5539.54	11079.08	22158.16

Table 4-12 Farmscoper results for each scenario, for WMC not already growing maize for AD.

Pollutant	25% increase	50% increase	100% increase	200% increase
Nitrate-N (t)	18.88	37.75	75.69	151.33
Phosphorus (t)	0.91	1.82	3.64	7.28
Sediment (t)	793.82	1587.64	3183.41	6364.91
Ammonia (t)	0.14	0.29	0.57	1.15
Nitrous Oxide (t)	1.35	2.7	5.42	10.84
Soil Carbon (000s t)	-9.01	-18.03	-36.14	-72.27
Energy Use (t CO_2)	1522.41	3044.81	6104.3	12205.16

Table 4-13 Farmscoper results expressed as change in pollutant per hectare of land displaced, split by WMCs originally growing maize for AD and those not doing so. The national footprint for each pollutant per hectare of agricultural land is also shown for context.

Pollutant	Maize for AD (per ha land displaced)	No Maize for AD (per ha land displaced)	National Footprint (per ha agricultural land)
Nitrate-N (kg ha^{-1})	2.36	14.88	27.6 [1]
Phosphorus (kg ha^{-1})	0.16	0.72	0.5 [1]
Sediment (kg ha^{-1})	120.75	625.98	218 [1]
Ammonia (kg ha^{-1})	-4.25	0.11	12.86 [2]
Nitrous Oxide (kg ha^{-1})	-0.44	1.07	4.2 [2]
Soil Carbon (t ha^{-1})	-3.23	-7.11	95.4 [1]
Energy Use (kg ha^{-1} CO_2e)	990.33	1200.36	1233 [1]

[1]*Calculated from Farmscoper predictions*

[2] *Calculated from emissions data taken from DECC 2013 UK Greenhouse Gas Emissions, Final Figures or National Atmospheric Emissions Inventory land area taken from Defra Agriculture in the United Kingdom (2013).*

EAgRET Results

Table 4-14 and Table 4-15 show the results for the change in emissions predicted by EAgRET for each of the four scenarios, for WMCs currently growing maize for AD and those not doing so, respectively. As described above, the emissions have been converted to kilograms per hectare of land displaced to allow direct comparison between the 'Maize for AD' and 'No Maize for AD' scenarios.

The detailed results for each WMC are provided in Appendix 3.

Table 4-14 EAgRET results for each scenario, for WMCs already growing maize for AD.

Pollutant	25% increase	50% increase	100% increase	200% increase
CO_2 (t)	-231.87	-463.75	-925.82	-1852.04
Nitrous Oxide (t)	-3.55	-7.1	-14.2	-28.4
GWP (t CO_2e)	-1289.88	-2579.77	-5158.01	-10316.4
Energy Use (TJ)	2.73	5.45	10.93	21.84
Acidification (t SO_4e)	-133.11	-266.22	-532.49	-1064.97
Eutrophication (t PO_4e)	-25.76	-51.53	-103.07	-206.14
N Balance (t)	-277.48	-553.95	-1110.37	-2220.63
P Balance (t)	-55.29	-110.57	-221.26	-442.49
Abiotic Resource Use (t Sbe)	1.11	2.22	4.44	8.88
N fertiliser (t)	-152.98	-305.97	-612.03	-1224.03
P fertiliser (t)	24.85	46.7	99.45	198.9

Table 4-15 EAgRET results for each scenario, for WMCs not already growing maize for AD.

Pollutant	25% increase	50% increase	100% increase	200% increase
CO_2 (t)	359.96	719.92	1444.05	2887.12
Nitrous Oxide (t)	-0.78	-1.55	-3.1	-6.21
GWP (t CO_2e)	128.73	257.46	518.94	1036.94
Energy Use (TJ)	6.42	12.84	25.74	51.46
Acidification (t SO_4e)	-40.25	-80.5	-161.14	-322.24
Eutrophication (t PO_4e)	-8.12	-16.23	-32.49	-64.98
N Balance (t)	-164.23	-328.47	-658.05	-1315.84
P Balance (t)	-39.19	-78.37	-157.04	-314.01
Abiotic Resource Use (t Sbe)	2.43	4.85	9.72	19.44
N fertiliser (t)	-50.65	-101.3	-202.8	-405.55
P fertiliser (t)	18.72	37.44	75.03	150.02

Table 4-16 EAgRET results expressed as change in pollutant per hectare of land displaced, split by WMCs originally growing maize for AD and those not doing so. The national footprint for each pollutant per hectare of agricultural land (where available) is also shown for context.

Pollutant	Maize for AD (per ha land displaced)	No Maize for AD (per ha land displaced)	National Footprint (per ha Ag. land)
CO_2 (kg ha^{-1})	-82.77	283.95	284.1 [1]
Nitrous Oxide (kg ha^{-1})	-1.27	-0.61	4.2 [1]
GWP (kg ha^{-1} CO_2e)	-461.08	101.98	-
Energy Use (MJ ha^{-1})	976.11	5061.03	-
Acidification (kg ha^{-1}SO_4e)	-47.60	-31.69	-
Eutrophication (kg ha^{-1} PO_4e)	-9.21	-6.39	-
N Balance (kg ha^{-1})	-99.25	-129.41	90 [2]
P Balance (kg ha^{-1})	-19.78	-30.88	6 [2]
Abiotic Resource Use (kg ha^{-1} Sbe)	0.40	1.91	-
N fertiliser (kg ha^{-1})	-54.71	-39.89	99 [3]
P fertiliser (kg ha^{-1})	8.89	14.75	18 [3]

[1]*Calculated from emissions taken from DECC 2013 UK Greenhouse Gas Emissions, Final Figures and land area taken from Defra Agriculture in the United Kingdom (2013).*
[2]*From DEFRA Report – Soil Nutrient Balances UK Provisional Estimates for 2014. Published July 23rd 2015.*
[3] *From British Survey of Fertiliser Practice 2014.*

4.3.3 Analysis of potential water quality impacts of increased maize production

The models predict increased emissions of diffuse pollutants, such as nitrate, phosphorus and sediment under the scenarios of increased production of maize for anaerobic digestion. This is predominantly due to the displacement of grassland (for WMCs already growing maize for AD 26% of the additional area is predicted to displace grassland and for WMCs not currently growing maize for AD, 69% of the additional area is predicted to displace grassland) , which has markedly higher per hectare net increases in emissions than displacement of arable crops.

The predictions of increase nitrate and phosphorus losses due to additional maize production could have potential consequences for water quality in English river systems and as a first step in understanding these potential consequences at WMC level, an analysis of the effect of increased nitrate and phosphorus loads on the concentrations of these pollutants in waterbodies within the WMC was done.

The analysis used data on observed and estimated in-river concentrations of nitrate-N and phosphorus from Defra project WQ0223. This data provides for each WFD waterbody (including upstream waterbodies) concentrations and loads of both nitrate N and phosphorus. In addition the data includes equations for calculating the percentage decrease in load required to reach key thresholds for water quality. These thresholds were 11.3mg N per litre for nitrate N and catchment specific thresholds for phosphorus that defined the border between a moderate or good rating for water quality (note that some waterbodies do not have defined thresholds for P and that the thresholds have been revised (in 2015) for the Cycle 2 assessment of the Water Framework Directive to provide site specific thresholds rather than catchment specific thresholds).

The equations used to calculate the percentage were adjusted so that they gave the percentage change in load that could be accommodated before the thresholds were exceeded. From this the percentage change in agricultural loading that could be accommodated before exceeding the threshold was calculated. Using these percentages two analyses were done with the following assumptions, which were made to convert the predicted changes WMC level to changes at waterbody level:

1. Analysis one assumed that the area converted to maize within the WMC was evenly spread across the total area of the WMC, so the area displaced per WFD waterbody was equivalent to the total area of maize converted multiplied by the area of the WFD waterbody divided by the area of the WMC
2. Analysis two assumed that all the area converted to maize within the WMC occurred within a single WFD waterbody (note that where the waterbody area was less than the area of maize converted, then it was assumed that the whole waterbody was converted to maize).

The results from the first analysis showed that where a waterbody is not already above the nitrate N threshold and not already classed as below good for Phosphorus then the increase in maize that might be expected in the water body (area-weighted from total increase in maize within the WMC) would not lead to any waterbodies changing their classification.

The results from the second analysis were similar for nitrate N, with no effect of the increased maize production on the number of waterbodies that would exceed the quality threshold. For phosphorus, the story is a little different, with some that are currently classed as of good quality waterbodies being tipped over the threshold into moderate or lower quality. The number of waterbodies within each WMC that are currently classed as good and the number that would be tipped over the threshold under the second scenario assumptions used.

It should be noted that these two scenarios effectively act as upper and lower extremes on what would be expected to occur. It is likely that the additional maize production within a WMC would be localised and not spread out evenly across the WMC, as assumed in the first analysis. However, it is unlikely that it would be restricted to a single WFD waterbody as assumed in the second analysis. Note also that for those WMCs where there is currently no maize production, the analyses described here have assumed that maize production would take place in these WMCs, with the implication that there is a large increase in nitrate N and phosphorus emissions due to a move from predominantly grassland systems to cultivated maize production. Finally, the analyses described here have assumed that maize could be produced on all land in the waterbody, i.e. we have not accounted for the area of arable land within the waterbody.

4.3.4 Impacts of an increase in maize production in WMCs already growing maize for AD

From the Farmscoper results (Table 4-11 and Table 4-13) there is a predicted increase in nitrate, phosphorus and sediment loss associated with an increased area of maize production. As WMCs already growing maize for AD are predominantly in areas that are suitable for growing arable crops, the majority of displacement will be happening to cereal crops. This is reflected in Table 4-7 which shows that the cereal crops have the highest proportion displacement (combined) in all scenarios. In contrast to the surface pollutants, emissions of ammonia and nitrous oxide, in the WMCs where maize is already being grown for anaerobic digestions, decrease with additional maize area, but for WMCs where there is currently no maize production for anaerobic digestion, then the emissions of these two pollutants increase with increasing maize production. This is most likely due to the displacement of grassland by maize, leading to an increase in the use of nitrate fertiliser on land where fertiliser inputs were previously very low. In addition, there is an increase in energy use associated with increasing the area of maize grown. Soil carbon is reduced across all scenarios.

From the EAgRET results (Table 4-14 and Table 4-16), there is a predicted reduction in Greenhouse Gas emissions for WMCs where maize for anaerobic digestion is already produced, but an increase in greenhouse gas emissions for those WMCs where maize for AD is not currently produced as the area of maize increases, which is consistent with what we see from the Farmscoper predictions. There is an increase in phosphorus fertiliser use as maize area increases, and a fall in nitrogen fertiliser use. These changes reflect the data from the British Survey of Fertiliser Practice (2014) that was used as inputs to both FarmScoper and EAgRET, which shows an increased amount of P fertiliser and a decreased amount of N fertiliser applied to maize compared to the most common arable crops (wheat, spring barley, oats and oilseeds). Despite the increased use of P fertiliser, the N and P balance is reduced across all scenarios, reflecting the different uptakes of nutrients by the crops.

Impacts of starting maize production for AD in WMCs not already doing so

In the Farmscoper results for these scenarios (Table 4-12 and Table 4-13), there is an increase in the losses of nitrate, phosphorus and sediment. There are also increase in both nitrous oxide and ammonia emissions, in contrast to the results for areas where maize for AD is already being grown. It is likely that the WMCs not already growing maize for AD have a good reason for doing so, such as climate or topography being unsuitable. Therefore it is likely that these WMCs are not as suited to arable crop production in general compared to the WMCs already growing maize for AD. The majority of these WMCs are in areas of the country dominated by grazing land which has a smaller environmental impact than maize and most arable crops in general. This could potentially be the cause of the increase in ammonia and nitrous oxide emissions (through increased application of fertilisers) and explains why the rise in runoff pollutants (N, P and sediment) is greater than in the scenarios where maize was already being produced. As in the previous scenarios, for areas where maize for AD is already being grown, energy use increased and soil carbon decreased with a move to producing more maize.

In the EAgRET results (Table 4-15 and Table 4-16), carbon dioxide emissions are increasing with increased area of maize grown whilst nitrous oxide emissions are decreasing. Whilst acidification and eutrophication are reduced, as for the scenarios for WMC where maize is currently being grown for AD, the magnitude of reduction is not as great. This is consistent with the view that moving from grassland to maize is likely to produce more runoff pollutants than moving from other arable crops to maize. The decrease in soil carbon was nearly double that of the areas where maize for AD was already being produced, which is in line with the theory that the differences are due displacement of permanent and temporary grassland because grassland provides greater carbon storage than annual crops.

The predicted emissions from FarmScoper and EAgRET reflect the use of different modelling approaches within the two tools. This is particularly relevant to nitrous oxide emissions, where FarmScoper uses a loss pathway approach to estimate the emissions from leached nitrate, whereas EAgRET uses a simple fraction leached coefficient in line with the IPCC 2006 guidelines for calculation of greenhouse gas emissions. These differences are what give rise to the difference in the nitrous oxide emissions for the scenario where maize is not currently being produced in the WMC. In general, the direction of change in emissions predicted by both tools is consistent.

Potential water quality impacts of increased maize production

The results of the analysis using assumptions representing lower and upper bounds of allocation of additional maize production to waterbodies showed that there was unlikely to be any impact in terms of increasing nitrate concentrations in rivers above quality thresholds. However, the situation for phosphorus was more complex and not straightforward. Therefore, we strongly recommend that a more detailed and refined analysis of potential tipping points is done, with emphasis on developing more detailed scenarios regarding the placement of additional maize production that account for planned construction of commercial and on-farm anaerobic digestion plants. In addition, the concentration assessment work from WQ0223 could be adapted to determine the increases in agricultural load of nitrate N and phosphorus that can be accommodated before the thresholds are reached, and the impact of the accommodation of load increases in downstream waterbodies.

Implications of modelling results for mitigation of impacts

The modelling results have shown that the main impacts occur through increases in pollutants such as nitrate, phosphorus and sediment. Therefore the mitigation options to deal with surface runoff and leaching identified and described in section 2.2 of this report will be important for reducing these impacts. The model predicted that the most significant impacts occur in WMCs where maize is not currently being produced for AD, these are areas which are dominated by grassland and are most likely to be less suitable for arable production. This suggests that mitigation options should be targeted in these areas, particularly in relation to the selection of appropriate displacements that minimise the environmental impacts of the displacement.

Given that one of the key drivers of the environmental impacts is the change in amounts of fertiliser applied, then there is potential for mitigation measures that reduce fertiliser inputs to reduce the overall environmental impact of increased maize production for AD, especially if the digestate is used on the same land, as this will reduce the fertiliser inputs and allow Phosphorus to be recycled within the system.

Table 4-17 The number of waterbodies in each WMC that have no threshold data for phosphorus, are currently predicted to be of good quality for phosphorus and the number of waterbodies that would no longer be of quality for phosphorus if all the maize increase predicted for the WMC occurred within that waterbody for each of the four maize production area increase scenarios (25%, 50% 100% and 200% increase)

WMC ID number	WMC Name	Number of waterbodies	Number of waterbodies with no threshold data	Number of waterbodies predicted to be of good quality	Number of waterbodies predicted to no longer be of good quality under the following maize production area increase scenarios:			
					25 percent	50 percent	100 percent	200 percent
1	Adur and Ouse	45	4	5	0	0	3	4
2	Aire and Calder	75	15	22	21	21	21	22
3	Alt and Crossens	11	3	5	0	2	4	5
4	Arun and Western Streams	35	7	9	8	9	9	9
5	Avon Bristol and North Somerset Streams	104	20	35	5	17	29	34
6	Broadland Rivers	60	15	25	17	22	23	24
7	Cam and Ely Ouse	69	7	25	23	23	25	25
8	Cherwell	34	2	6	5	6	6	6
9	Colne	16	0	6	0	0	0	1
10	Combined Essex	66	10	10	10	10	10	10
12	Evenlode	16	0	6	5	6	6	6
13	Cuckmere and Pevensey Levels	17	2	2	1	1	2	2
14	Darent	5	1	4	0	0	0	1
15	Derwent Derbyshire	39	1	16	8	13	15	15
16	Derwent Humber	70	6	37	1	12	23	27
17	Derwent North West	33	2	15	9	13	15	15
18	Don and Rother	70	18	10	8	8	9	10
19	Dorset	67	7	32	15	24	30	32
20	Douglas	15	5	4	2	4	4	4

WMC ID number	WMC Name	Number of waterbodies	Number of waterbodies with no threshold data	Number of waterbodies predicted to be of good quality	Number of waterbodies predicted to no longer be of good quality under the following maize production area increase scenarios:			
					25 percent	50 percent	100 percent	200 percent
21	Dove	26	6	2	1	1	2	2
22	East Devon	80	2	28	25	27	27	28
23	East Hampshire	11	1	8	1	3	5	8
24	East Suffolk	43	3	11	11	11	11	11
25	Eden and Esk	95	7	53	50	51	53	53
26	Esk and Coast	21	4	9	7	8	8	8
27	Avon Hampshire	39	9	28	20	23	24	26
28	Hull and East Riding	48	15	15	0	0	0	2
29	Idle and Torne	37	6	3	3	3	3	3
30	Irwell	28	9	9	0	1	5	6
31	Isle of Wight	10	2	3	1	1	3	3
32	Kennet	29	5	15	11	14	14	14
33	Kent and Leven	36	2	31	22	28	29	31
34	Loddon	19	1	2	1	2	2	2
35	London	30	5	7	0	0	1	2
37	Louth Grimsby and Ancholme	32	9	13	12	13	13	13
38	Lower Trent and Erewash	73	15	10	9	10	10	10
39	Lune	41	0	31	23	26	28	29
40	Lower Thames	11	1	2	0	0	1	2
41	Medway	51	3	9	1	5	8	9
42	Mersey Estuary	24	1	10	2	8	10	10
43	Dee	9	0	0	0	0	0	0
44	Mole	19	3	6	0	1	6	6
45	Nene	60	5	19	19	19	19	19
46	New Forest	16	0	12	4	10	10	11

WMC ID number	WMC Name	Number of waterbodies	Number of waterbodies with no threshold data	Number of waterbodies predicted to be of good quality	Number of waterbodies predicted to no longer be of good quality under the following maize production area increase scenarios:			
					25 percent	50 percent	100 percent	200 percent
47	North Cornwall, Seaton, Looe and Fowey	45	3	31	0	0	0	5
48	North Devon	92	9	28	3	13	22	25
49	North Kent	1	0	1	1	1	1	1
50	North Norfolk	6	0	4	3	3	4	4
51	North West Norfolk	10	4	2	0	0	0	1
53	Northumberland Rivers	76	13	23	0	0	4	10
55	Old Bedford and Middle Level	6	5	0	0	0	0	0
56	Ribble	70	4	34	30	33	33	34
57	Roding, Beam and Ingrebourne	13	4	2	2	2	2	2
58	Rother	30	4	3	3	3	3	3
59	Severn Uplands	26	14	0	0	0	0	0
60	Severn Vale	45	14	5	3	3	4	5
61	Severn Middle Shropshire	34	10	0	0	0	0	0
62	Soar	46	5	3	3	3	3	3
63	South and West Somerset	100	18	25	11	18	23	24
64	South Devon	58	9	38	0	1	12	24
66	South Essex	3	0	1	0	0	0	1
67	South West Lakes	29	3	22	1	7	13	19
69	Trent Valley Staffordshire	37	11	3	1	3	3	3
70	Stour	20	2	13	5	6	10	13
71	Swale, Ure, Nidd and Upper Ouse	117	18	37	0	0	0	0
72	Tamar	52	6	22	0	0	3	9
73	Tame Anker and Mease	47	10	5	5	5	5	5
74	Tees	76	8	25	14	18	23	25

WMC ID number	WMC Name	Number of waterbodies	Number of waterbodies with no threshold data	Number of waterbodies predicted to be of good quality	Number of waterbodies predicted to no longer be of good quality under the following maize production area increase scenarios:			
					25 percent	50 percent	100 percent	200 percent
75	Teme	41	22	5	3	4	5	5
76	Test and Itchen	30	2	23	4	10	17	18
77	Thame and South Chilterns	32	2	9	4	7	8	8
80	Till	20	2	14	12	13	13	14
81	Tyne	103	15	63	0	0	18	42
82	Upper and Bedford Ouse	88	5	25	2	17	22	25
84	Upper Lee	24	6	9	8	9	9	9
85	Upper Mersey	44	8	13	4	9	12	13
87	Cotswolds and the Vale	64	8	24	21	24	24	24
88	Avon Warwickshire	75	22	6	5	6	6	6
89	Waver or Wampool	9	0	1	1	1	1	1
90	Wear	56	16	10	10	10	10	10
91	Weaver and Gowy	62	1	8	0	0	2	5
92	Welland	37	12	7	5	6	7	7
93	West Cornwall and the Fal	48	5	31	14	24	29	31
94	Wey	31	2	10	2	7	9	10
95	Wharfe and Lower Ouse	44	8	21	3	9	15	17
96	Witham	78	20	26	26	26	26	26
97	Severn Middle Worcestershire	43	8	10	0	0	4	9
98	Wye	50	3	15	10	11	12	13
99	Wyre	14	3	3	0	1	3	3
100	Tweed	1	0	0	0	0	0	0

4.3.5 Summary

The analysis of June Agricultural Survey data, to assess which agricultural production types are displaced by maize production for use in anaerobic digestion, found that, there is extremely limited preferential displacement of crops by maize being grown for anaerobic digestion with the majority of crops being displaced in direct relation to their area. However, wheat in arable systems and permanent grazing in livestock systems are less likely to be displaced than other crops, with triticale in livestock systems being more likely to be displaced. This may be unexpected, but is perhaps not surprising when we consider that the net margin for maize production for anaerobic digestion is higher than other crops (Vogel, Hellawel & Collins, 2011). Therefore as displacement of any crop by maize should have an economic benefit, the choice of crop to displace is likely to be determined by a range of factors and individual preference rather than a single dominant factor, making preferential displacement less likely. However, due to the small sample size, the results must be treated with appropriate caution.

The analysis of the environmental impacts assumed that no digestate was returned to land and has shown that in general displacement of other crops by maize in areas where maize is already being grown for AD results in reduced emissions of greenhouse gases and ammonia and increased emissions of diffuse pollutants such as nitrate, phosphorus and sediment, which were less than the current national average loss per hectare of each of the pollutants. The reduced emissions of greenhouse gases and ammonia is most likely to be a result of the reduction in the amount of nitrogen fertiliser when replacing other crops with maize. The environmental impacts analysis assumed that digestate is not recycled to land. Recycling the digestate will reduce P-requirements and is likely to increase NH_3-emissions from application relative to baseline scenarios, impacts on NO_3-N leaching will depend upon application timing.

For those Water Management Catchments (WMCs) where there is no current production of maize for anaerobic digestion, the predicted net emissions for the non-gaseous diffuse pollutants (nitrate, phosphorus and sediment) show a much greater increase than for WMCs where maize is already being grown. For the greenhouse gas emissions, there is an increase in the amount of ammonia and nitrous oxide emitted, plus an increase in carbon dioxide emissions. This is most likely due to the fact that for those WMCs where maize is not currently being grown, there is a very high displacement of permanent and temporary grass as these WMCs are dominated by grassland, with 69% of the predicted new maize area displacing grassland.. Since grass production uses much lower fertiliser application rates than maize, then any change to maize would lead to an increase in direct, indirect and embedded pollutant emissions associated with fertilisers.

An analysis of the potential impacts of the predicted changes in nitrate and phosphorus losses on water quality suggests that the drinking water quality thresholds for nitrate would not be exceeded even with a 200% increase in nitrate loads. For phosphorus, the results suggest that impacts could occur, but that these would be highly localised. The results should be treated with caution as the analysis used simple assumptions to produce potential upper and lower extremes of land displacement within individual waterbodies from WMC level data. In addition, for phosphorus, the analysis used catchment specific thresholds and these have recently been replaced with site specific thresholds as part of the Cycle 2 assessment of the Water Framework Directive.

5 Evidence from AD plant case studies

This work package focused on four cases studies of anaerobic digestion (AD) plants in England and Wales to consider the absence or presence of evidence of changes in land rental prices in the vicinity of AD plants. It is based on primary data in the vicinity of these digesters, from interviews with AD plant operators and supplying farmers as well as key local stakeholders such as land agents and farming organisations. It supplements the analysis in chapter 2.1 which considers trends in agricultural land rental price data over time at a national and regional scale (England only). This evidence is based on a small sample of four case studies and is illustrative rather than representative.

Evidence on the land rental impacts, the case studies also provide valuable insight into the motivations and perceptions of plant-owners and farmers supplying maize as a feedstock. They also captured data on the economics of plant operation and maize production (as available), and sought evidence and opinions on the environmental and community impacts of these AD plants.

In addition views were collected from ten farmers nationally and are summarised on the basis of geography to reflect the distinct systems (both in terms of AD scale and feedstock mix, and enterprises displaced).

5.1 Methods

Plant selection

Case study plants were selected using criteria outlined by Defra in the research specification and detailed below (Table 5-1).

Table 5-1: AD plant selection criteria

Capacity	Feedstock	Number of case studies
Above 1 MW	Crop only	2
Above 140 kW	Mixed	1
Below 80 kW	Mixed	1

After AD plants had been categorised by size, further selection was based on:

- Locality – to ensure coverage of the different farming and geoclimatic contexts across England and Wales.
- Commission date – to ensure plants had been commissioned for long enough to be operational and impacts assessed.
- Clusters – to understand how a concentration of AD plants in an area affects impacts.

Case study interviews

After selection of the AD site, plant operators and farmers were contacted to secure their agreement to take part in the study and to undertake face to face interviews. Six plants were contacted initially, of which one did not wish to take part and another no longer used maize as a feedstock.

For each case study, the following key stakeholders were approached:

- AD plant operator – to gather evidence on the operation and economics of the AD plant.
- Growers of feedstock for the AD plant – to gather evidence on the management of the crop, its fit within the farm system and economic returns.
- 2 Land Agents in the local area – to gather evidence and views on land rental impacts.

- NFU local representative – to capture the union's perspective on land rental and environmental impacts of maize production for AD in the case study region.
- Environment Agency – to capture the agency's perspective on environmental impacts of AD in the local area.
- County Council – to capture the Council's perspective on social impacts of AD in the local area.

If stakeholders were unable to participate in a face to face interview, a phone interview was conducted. At a national level the CLA, NFU and a University researcher were contacted to aid understanding of national trends in the farming community and national impacts of increased maize growth on biodiversity.

Additionally, views were sought from farmers outside the maize AD supply chain. It was planned that this would be in the form workshops but not enough farmers were able to attend and responses were recruited using email networks and social media. Respondents completed a questionnaire via email or telephone interview.

5.2 Overview of case studies

An overview of the case studies is set out below. It should be acknowledged that this work was undertaken on a small sample to illustrate practices and impacts and is not necessarily representative of AD plants across England and Wales. The four case studies are characterised as follows:

Case Study 1: Crop only digester of at least 1 MW in size. This plant is run by a commercial operator in the renewables sector and based in the East of England. It was commissioned in 2013, producing 2.2-2.4 MW electricity for the national grid. The plant uses 33k tonnes of feedstock per annum, of which 97% is maize with small amounts of hybrid rye, grass and energy sugar beet. The output is combined heat and power (CHP). All feedstock for the plant is supplied by a local grower group, mainly focussed on vegetable crops, and is responsible for sourcing land, buying inputs, drilling and harvesting.

Case Study 2: Crop only digester of at least 1 MW in size. This biogas plant is run by a farmer-owner operator and is based in the East of England. It commissioned in 2012, producing 1.4 MW electricity. The plant uses 24k tonnes of feedstock per annum, of which 12k tonnes is maize, 8k tonnes whole crop rye and 4k tonnes is grass silage. The output is combined heat and power (CHP). The plant is run as a joint venture partnership between two farmers with one contracted to supply all the feedstock. In addition to feedstock grown on the owner-operator's farm, up to 11 local farms supply the plant.

Case Study 3: Mixed agricultural feedstock digester of at least 140 kW in size. This is a 2MW farmer-owned and run AD plant based in the West Midlands that utilises a mixed feedstock of waste and crop feedstock. The AD plant was built in 2012 and is a semi-plug flow digester that consists of 2 Combined Heat and Power (CPH) units – 500 kW and 800kW – that are designed to have a potential capacity of 1300kW/hr. The farm extends to 657 hectares and is mainly arable with 40 hectares of grassland. Enterprises include six feedstock crops for the AD plant.

Case Study 4: Mixed agricultural feedstock digester of at least 140 kW in size. This farmer-owned and run AD plant is based in the south west of England. The AD plant is an 80MW plant with feedstock consisting of dairy slurry, poultry litter and maize. The holding where the AD plant has been developed is rented and extends to 81 ha of land with an additional 49 ha of land owned and is half arable and half permanent pasture.

Full case study details are reported in Appendix 3.

Motivation for investment in AD and using maize as a feedstock

The motivations to build an AD plant or be involved in delivering feedstock varied widely across the case studies. Key reasons for investment in AD included improving economic stability and the diversification of the farm businesses in the context of volatile food commodities markets. One of the larger plants is not farmer-owned. Other drivers include, better slurry management, improved weed control, loss of other markets e.g. for sugar production and the generation of "green energy".

Motivations for growing maize were different for the large eastern plants and smaller western region plants. In the east the main aim was to introduce a crop that suited the light soils in the area and could fit into a crop rotation, possibly improving yields of other crops in the rotation (carrots and wheat). In the west, maize was grown as an addition to other feedstocks on the basis that it had a high energy value and the farmer was familiar with the crop. The farmer in the West Midlands did indicate he would like to use food waste in the plant, but getting the appropriate permits from the Environment Agency (EA) was complex.

Digestate

All digestate from the smaller plants in the south-west and west midlands case studies is utilised on farm. The growers for the larger plants receive a proportion of the digestate in return for the feedstock. The digestate is free of charge with only haulage being paid for, incentivising more local supply of feedstock.

All case study farmers growing maize report a decrease in the amount of artificial fertiliser used on farm due to using the digestate. Other positives of using the digestate include better soil structure, an increase in yield and potentially killing diseases in manure and slurry that may have previously been spread straight on to the field. Several stakeholders across the case study sample plants acknowledged the importance of good management and storage of digestate for optimum benefits to the farming environment.

Displacement of crops

Displacement of crops on the farms that feed the smaller AD plants was easy to quantify. For example, 16 hectares of winter wheat was displaced for maize in the South West case study. In the West Midlands case study, winter cereals and (historically) sugar beet were displaced with an increase in crop diversity, notably the introduction of spring cereals. Based on evidence from the farmers and land agents in the East of England, maize has replaced wheat, spring barley, potatoes, and sugar beet in arable rotations and has been useful in weed control in areas with pernicious blackgrass.

In all of the case study areas none of the consultees expressed a concern about maize currently reducing livestock numbers but there was acknowledgement that AD was displacing fodder in terms of crop use.

5.3 Economic impacts

The economic case for farm AD plants is based on income from the sale of electricity, subsidies on electricity sold, savings on electricity bills and savings on fertilisers on the farm. The operators in the four case studies report positive economic returns but as three are farmer-owned, they also value wider benefits in terms of diversification and stability of income and benefits to the farming system. The larger plants also report increases in direct employment; the largest plant employed an extra 4 full time and 33 seasonal workers but the smallest plant did not employ any additional labour. An increase in the use of contractors was also recognised in all areas, by the majority if stakeholders.

In terms of economic returns for farmers contracted to supply maize as a feedstock, those interviewed report that margins are higher than from winter and spring-sown cereals. In the east of England, maize harvested in October offers a good entry for winter wheat to be planted. Farmers and land agents noted several indirect economic effects, including increased yields from other crops in rotation with maize and a decrease in the cost of blackgrass control. Some reported improved utilisation of the labour due to the timing of fieldwork and generally there was no requirement for additional equipment. Where digestate is returned to the grower, there may also be a benefit in terms of soil organic matter.

Land rental prices

Impacts on land rental prices appeared to vary greatly across the case studies. In the East of England much of the land where maize is grown for AD is owned and the crop is normally grown in rotation. The general view by those interviewed in the case studies is that land prices have increased. However, it is difficult to separate the impact arising from maize grown for AD and multiple other factors, including a general increase in demand for land for agriculture (for sugar beet, vegetables and outdoor pigs) and for other uses e.g. solar energy development.

The West Midlands is a very diverse farming region and competition for land is already relatively high. As in the East of England, land rental prices are higher where there are vegetable, potato and dairy farms. The price of cereals is a common driver of land rent prices in the area as it can expand and contract across years without affecting the supply chain. There is an overall observation that over the last 2-3 years there has been an increase in land rental prices but this trend has reduced in the last year. Some associate this entirely with movements in cereal prices but other stakeholders have suggested that this was due to AD plants paying above market value prices to secure land for maize feedstock, which have subsequently stabilised this year at a much lower rate. This implies that short-term land rental markets are very sensitive to market drivers.

In the South West, stakeholders interviewed were more willing to attribute higher land rental prices to the impact of AD plants. Several commented that there were localised effects around the AD plants (increased where clusters are seen), but currently no major impact on the overall region. Again initial high prices paid to secure rented land were associated with the first year of the AD plant being commissioned, with a subsequent stabilisation of rental prices. In this region many dairy farmers have expanded by the renting land (often on short term contracts) which may be part of the reason for a larger impact. Other high value crops are less significant in the area.

In all regions represented by the case studies there were concerns about the impact of AD plants on land rental prices. Across the case studies there is a general view from stakeholders interviewed that when AD plants are commissioned, there is a localised increase in land rental prices due to plant owners paying above market value rental prices for land to use to grow maize as feedstock. This often subsequently stabilises. The impacts of AD on land rental prices is conflated with other drivers such as high value crops and localised expansion in the dairy sector, making it difficult to isolate impact.

5.4 Environmental impacts

Impact on soil erosion and structure

One of the largest variations between the regions studied is impact on soils. In the East of England the land is relatively flat with soils suited to cultivation and able to accommodate late harvesting e.g. for potatoes or sugar beet due to lower rainfall. There has also been a proactive effort by one of the case study plants in the east to help growers implement best practice through regular input from the Maize Growers Association.

In the West Midlands case study, the farmer commented that maize has (historically) replaced sugar beet which the farmer believes had worse impacts on soil erosion and structure. In the region the EA report several significant soil erosion events not associated with the case study plant which have resulted in road closures as well as sediment deposits in residential areas. The EA also express concerns about a lack of rotations for maize and the use of marginal ground not suitable for maize cropping. The EA and Local Authority are working together to provide events to help with mitigation of these problems.

In the South West, the EA commented that the pollution risk is higher due to soil type, slope and annual rainfall. As maize is commonly grown for fodder on mainly for dairy farms in the region, it was difficult to separate the impacts from growing maize for fodder and maize for AD.

Across the case study regions all stakeholders interviewed were aware of the damage that could be caused to soil stricture and erosion through maize cropping. The impact of increasing the amount of maize grown in regions is very different due to variation in soils, land slopes and rainfall. The EA believes mitigation to decrease impacts of maize on soil is vital and would like to see this implemented when the farmer begins to grow maize and not after soil erosion and damage has already taken place.

Water quality

Water quality was a large concern of the EA in all regions. An increase in soil erosion can result in the movement of soil sediment and nutrients such as nitrogen and phosphorus into the watercourses. Incidents have been reported to the EA regarding digestate storage and management. Mostly these have been a result of inadequate storage of digestate or feedstock.

Impact on biodiversity

Few stakeholders interviewed were confident enough in their knowledge of changes in biodiversity to share their views. Opinions included, maize winter stubble not being as valuable as cereals crops in winter and that agri-environment measures and mitigation techniques could reduce biodiversity impacts.

5.5 Summary of maize AD impacts

The four case studies have highlighted significant variation in the impact of maize cropping for AD between based on scale, location and management. Economic impacts are closely associated with the size and feedstock of the plants. Environmental impacts are largely associated with regional differences particularly in soil type, slope and rainfall. Impacts on land rental values have been attributed to an overall increase in competition for land, including other agricultural crops and renewables as well as AD plants. A key theme from all regions is the steep learning curve for those growing maize for AD, both in terms of land rentals being paid and environmental mitigation. In particular, the impact on land rental prices may be time-limited to some extent as land for maize is initially secured, with rental values reducing in subsequent years. It appears a large opportunity lost is in the use of the heat produced from the CHP plants.

The limited consultation with farmers outside the AD supply chain (10 respondents) reflects the views of those who have negative experiences and/or opinions of maize for AD who have been motivated to comment. As such, these comments do not necessarily represent the experiences of the wider population of farmers operating in proximity to AD plants. The majority of respondents reported an increase in land rental prices on short term land rental contracts, especially 3-5 year FBTs. Some have a fundamental issue with the policy approach of supporting crops for energy which displace food.

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7 Appendix 1: Testing the hypothesis that bioenergy cropping for anaerobic digestion (AD) is impacting land rental prices in England and Wales

The government has an ambition to increase energy from waste through anaerobic digestion (AD) at all scales. AD can avoid the greenhouse gas emissions from sending wastes to landfill and can improve nutrient management on farms. As well as renewable energy AD produces digestate, a material that can, to some extent, replace inorganic fertilisers and avoid the greenhouse gas emissions associated with their production.

There are, however, concerns that the further development of AD plants may drive a change in farming practice from food to bioenergy cropping, where the latter decreases availability of land for food production and influences land rental values. The development of AD plants is therefore of interest in the debate about security of food and energy supplies.

Regression-based approaches have been used here to quantitatively explore the financial implications of AD plants through testing the hypothesis that bioenergy cropping for AD is impacting land rental prices.

7.1 Materials & methods

7.1.1 Materials

The following spatial analysis explores the relationship between agricultural land rental prices and several proxies (variables of interest) associated with the production-conversion process of energy crops in England and Wales, with adjustment for the influence of general confounding variables. Confounding variables are background factors that are not of direct interest, but can change the magnitude of the relationship between rental prices and the variables of interest. The analysis was conducted within the Ordnance Survey Great Britain (OSGB) 10 km^2 lattice grid, a resolution which was determined by the Farm Business Survey (FBS) data, used as the dependent variable. Table 7-1 summarises origins of datasets, processing procedure and key data characteristics.

A logarithmic-10 transformation was applied to the value of "Total Agricultural Land Rental" (£/ha) at each OSGB 10 km^2 cell, to provide a normal distribution as determined by the Kolmogorov-Smirnov goodness-of-fit test at the 95% significance level.

General confounding variables were selected in accordance to the criteria of Kostov's (2009) spatial quantile regression model of agricultural land prices in Northern Ireland, which accounted for land quality and connectivity metrics (i.e. proximity to urban area, and road-network). Several other explanatory variables specifically relating to the production-conversion process of energy crops were added following consultation with an expert panel at Defra. Finally, a measure of local socio-economic wealth was included as trends in land rental agreements at a national level were observed to follow the rate of inflation for consumer goods and services (Table 1-1).

Independent variable suitability was initially assessed by Pearson's R and Spearman's Rho correlation significance with the dependent variable at a national level (Table 7-1). All of the main independent variables (X_1-X_8) showed some degree of correlation with land rental prices, with the exception of proximity to an urban location. From the size of the correlation coefficients, no single variable seems to have controlling influence on the price of agricultural land rental at a national level; rather there are a multitude of factors at play, with location-specific impacts. Because correlation coefficients simply quantify the level of association between two variables, further analysis is needed to understand any casual relationships between the independent and dependent variables.

Prior to the construction of the regression models, a Variance Inflation Factor (VIF) diagnostic was collectively conducted across the independent variables using the 'usdm 1.1-12' [R] package. VIF values smaller than five were deemed to indicate no collinearity issues, VIFs between five and ten indicated moderate collinearity, and VIFs ten or greater indicated a serious issues (Schuenemeyer and Drew, 2011). No issues of multicollinearity were detected (Table 7-2).

Table 7-1 Information in relation to the origin, processing procedure, and key characteristics for variables of interest in the relationship between agro-economic stimulators and agricultural land rental prices, in the 682 measured OSGB 10 km² grid cells

SOURCE	DATASET (S)	VARIABLE	YEAR	DATA PROCESSING	MODEL	MEAN (RANGE)	XY CORRELATION	
							R	RHO
Defra & WG	FBS	LOG_{10} "Total Agricultural Land Rent Value" (£/ha)	2012	$\mathbf{LOG_{10}}\left[\frac{\sum \textbf{Holding Weighted Rent } (£)}{\sum \textbf{Holding Weighted Area } (\textbf{ha})}\right]$ Excluding rental agreements for holdings: • *Containing "Buildings" or "Other Assets"* • *Conducting "Horticultural" or intensive farming practices ("Pigs" or "Poultry")* • *With an area <2ha* Removal of low value OSGB 10 km grids (<£50 per ha) acting as normal distribution outliers	Y	2.2 (1.7 - 2.9)	--	--
		Land occupied by Full Agricultural Tenancy (FAT) Agreements (%)	2012	Percentage of the total rented land area within each OSGB 10 km² cell, occupied by holdings operating under a FAT agreement	X_1	16.2 (0.0 - 100.0)	-0.08**	-0.07*
	JAC & WG-LPIS	Maize Coverage (ha)	2013	Zonal Summation of nested OSGB 5 km² grids to OSGB 10 km² outputs	X_6	143.5 (0 - 1192.0)	0.03	0.06**
Natural England & WG	ALC	Agricultural Land Classification (ALC)	E: 2010 W: 1988	Intersection of a continuous mapped surface (1:250,000 Scale) to OSGB 10 km² outputs. ALC values were summarised by area apportionment (i.e. A grid with 50% Grade 1 and 5, is deemed Grade 3)	X_2	3.2 (1.1 – 5.0)	-0.15***	-0.15***
OS	MERIDIAN 2	LOG_{10} "Proximity to the motorway network" (km)	2014	Average 'Near Analysis' of 10x10 lattice gridded sample points (N=100), for each OSGB 10 km² cell.	X_3	1.3 (0.1 – 2.2)	0.02	0.06*
ONS	2011 CENSUS	LOG_{10} "Proximity to urban area + 1" (km)	2011		X_4	0.8 (0.0 – 1.7)	0.01	0.07
		OSGB 10 km Carstair's Index of Deprivation (z-score)	2011	Intersection of ONS 2011 Census Output Area (OA) geographies (1:250,000 Scale) to OSGB 1 0km² outputs. The fraction of intersected area acts to redistribute the following census variables (Land based allocation):	X_5	-0.4 (-6.0 – 10.6)	0.03	0.10***

				• *Vehicle Ownership (KS404EW)* • *Male Economic Activity (KS601EW)* • *Overcrowding (QS409EW)* • *Social Grade D/E (QS611EW)* The Summation of census variable z-scores provide values of relative socio-economic status at the OSGB 10 km^2 level (Carstair & Morris 1991).				
LANDIS	NATMAP VECTOR	Agricultural land suited for Maize Crops (%)	2014	Intersection of a continuous mapped surface (1:250,000 Scale) to OSGB 10 km^2 outputs	X_7	34.3 (0 - 100.0)	0.09**	0.08***
Defra	WRAP	LOG_{10} "Proximity to Anaerobic Digestion (AD) Plant" (km)	2012	Average 'Near Analysis' of 10x10 lattice gridded sample points (N=100), for each OSGB 10 km^2 cell. In 2012, 41 AD Plants were operational across England & Wales that were not fed by municipal waste.	X_8	1.5 (0.6 – 2.3)	-0.06	-0.04
		Nearest AD Plant Output (kWe)	2012	Calculated as the average Kilowatt energy (kWe) value of the nearest AD Plant to each of the 100 lattice gridded sample points in a given OSGB 10 km^2 cell.	$X_{8\text{-INT A}}$ (Interaction)	597.8 (3.0 – 3000.0)	0.04	-0.02
		Influence of "Crop" fed AD Plants (%)	2012	Using a 'Near Analysis', N/100 Points in a given OSGB 10 km^2 cell were summated where "CROP ONLY" AD Plants are closest. This output value relates to the percentage of a grid influenced by crop fed AD Plants.	$X_{8\text{-INT B}}$ (Interaction)	17.6 (0.60–100.0)	-0.01	-0.05

XY Correlation defined at a national level by R (Pearson 1895) and Rho (Spearman 1904) coefficients

* Correlation significant at the 0.10 level (2-tailed); ** Correlation significant at the 0.05 level (2-tailed); *** Correlation is significant at the 0.01 level (2-tailed)

Table 7-2 Variance Inflation Factor (VIF) quantifying the level of independence between agro-economic explanatory (independent) variables

Model Variable	X_0	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	$X_{8\text{-INT A}}$	$X_{8\text{-INT B}}$
VIF	--	1.04	2.01	1.72	2.09	1.30	1.17	1.96	1.26	1.62	1.40

Linear correlation coefficients ranges between: 0.0 ($X_{8\text{-INT B}}$ ~ X_1) to 0.5 (X_4 ~ X_3)

7.1.2 Regression methods

Ordinary least squares (OLS)

OLS regression methods are traditionally used to define the variation of a dependent variable in terms of a fixed response gradient for each individual explanatory variable:

$$\mathbf{y} = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1\mathbf{X}_1 + \boldsymbol{\beta}_2\mathbf{X}_2 + \ \ldots\ \boldsymbol{\beta}_N\mathbf{X}_N + \boldsymbol{\varepsilon}$$

(Eq.1)

Where **y** is the dependent variable (LOG_{10} transformed FBS land rental agreement), $\mathbf{X_1, X_2 ... X_N}$ are the independent variables (JAC maize crop cover, proximity to AD plant, etc.), $\boldsymbol{\varepsilon}$ is the residual value, $\boldsymbol{\beta_0}$ is the intercept, and $\boldsymbol{\beta_1, \beta_2 ... \beta_N}$ are regression coefficients relating to their respective independent variables. As such, OLS models describe average (or global) parameter estimates, which are assumed to operate uniformly across space. Yet, the assumption of a uniform modelled relationship over space would be quite misleading if such relationships are intrinsically different across space.

Spatial error model (SEM)

When spatial dependence is detected in the residuals of conventional multivariable regression, either a spatial lag approach or a spatial error approach can be used to incorporate such effects in the regression model. The spatial lag model assumes that autocorrelation is only in the dependent variable (land rental value) and is appropriate when the focus is on the assessment of the existence and strength of spatial interaction. The spatial error model assumes that regression errors are spatially dependent and that the included explanatory variables do not fully explain spatial autocorrelation. The latter approach is conceptually more appropriate where: [1] spatial heterogeneity (the uneven geographic distribution of observations) occurs but the relationships among specified variables are considered stationary; [2] missing often unquantifiable variables have a distinct spatial footprint; [3] observation density varies. Here, spatial dependence enters through the errors (nuisance) rather than through the systematic component (substance), thus correcting for the potentially biasing influence of spatial autocorrelation resulting from the use of geographic data.

SEM focuses on parameter estimation for independent variables of interest in the systematic part of the model, and essentially disregards the possibility that observed spatial correlation may reflect something more meaningful. In the spatial error model, the conventional OLS regression equation is augmented by a term ($\boldsymbol{\lambda W \xi}$) that represents the spatial structure ($\boldsymbol{\lambda W}$) of the spatially dependent error term ($\boldsymbol{\varepsilon}$). It can be summarised as follows (Ward and Gleditsch 2008):

$$\mathbf{y_i} = \mathbf{X_i}\boldsymbol{\beta} + \boldsymbol{\lambda}\mathbf{W_i}\boldsymbol{\xi}_\mathbf{i} + \boldsymbol{\varepsilon}_\mathbf{i}$$

(Eq.2)

Where $\boldsymbol{\lambda}$ represents the coefficient for spatially auto-correlated errors (spatial autoregressive coefficient), $\mathbf{W_i}$ is the spatial weights matrix of neighbouring OSGB 10 km^2 observations **j** in relation to the ego observation cell at location **i**, $\boldsymbol{\varepsilon}$ represents the random error term in the OLS model, and $\boldsymbol{\xi}$ is the spatially independent error term. SEMs were created using the ‘spdep 0.5-88’ [R] package, the parameters of which are estimated using the maximum likelihood method.

Akin to OLS modelling, SEM outputs return fixed coefficients describing the average rate of influence throughout the dataset (at a national level) attributed to an incremental increase in an independent variable. The construction of ’global’ coefficients is of particular relevance when seeking to inform policy at a national level. Policy effectiveness at the national level may be obtained where there is a significant relationship representative of the typical national response; but there is increased risk of ineffective national policy where there are increasingly localised relationships.

Multilevel modelling

Multilevel regression models are a class of statistical models developed for the analysis of data structures with nested (hierarchical) sources of variability. Observations made within a cluster are usually assumed to be dependent, whereas clusters themselves are assumed to be independent of one another. The general idea of a multilevel model is that this hierarchy is taken into account. This is achieved through the addition of random effects to traditional regression models, so as to define the covariance structure of the data. In essence, the random effects remove unmeasurable spatial influences (white noise) from the fixed parameter estimates.

To address issues of spatial non-stationarity, rental information contained in OSGB 10 km^2 grid cells were initially nested by regional location. In this two-level response model, broad structures of spatial influence were included through the addition of a second intercept unique to each region. The linear random intercept multilevel model is defined as:

$$\mathbf{Y_{ij} = X_{ij} * \beta + Z_{ij} * b_j + \varepsilon_{ij}} \qquad \mathbf{i = OSGB\ 10km^2\ Observations} \quad \mathbf{(Level\ 1)}$$
$$\mathbf{j = Regional\ Geography} \quad \mathbf{(Level\ 2)}$$

(Eq.3)

Where **Y** represents the dependent variable recorded as the price of agricultural land, $\mathbf{X_0, X_1 \ldots X_N}$ are the fixed independent variables (e.g. intercept, ALC classification, etc.) with corresponding fixed effects parameter estimates $\mathbf{\beta_0, \beta_1, \ldots \beta_N}$. Random effects occurring at the regional level are described through the variable **Z**, which has a random effect parameter estimate **b**. Residual values of the complete model are recorded as $\boldsymbol{\varepsilon}$. It is assumed that **b** and $\boldsymbol{\varepsilon}$ are uncorrelated random variables with zero means and covariance matrices **G** and **R**, respectively. Thus, the expectation and variance **V** of the observation vector **Y** are (Brown and Prescott 2006):

$$\mathbf{E[Y] = X\beta}$$
$$\mathbf{Var[Y] = V = ZGZ^T + R}$$

(Eq.4)

Unbiased estimates of variance and covariance parameters were obtained through the maximum likelihood (ML) estimation procedure (Brown and Prescott 2006, Section 2.2.1, p47), optimised through the penalised iteratively reweighted least squares (PIRLS) algorithm. Upon defining suitable variance and covariance parameters it is possible to obtain $\hat{\boldsymbol{\beta}}$ which is the '*best linear unbiased estimator'* of **β**, and $\hat{\boldsymbol{b}}$ the '*best linear unbiased predictor'* of **b** (Brown and Prescott 2006):

$$\mathbf{\hat{\beta} = (X^T V^{-1} X)^{-1} X^T V^{-1} Y}$$
$$\mathbf{\hat{b} = GZ^T V^{-1}(Y - X\hat{\beta})}$$

(Eq.5)

If significant spatial structures are identified from the preceding Spatial Error Model (SEM) modelling strategy, these can form a third level of nesting to better disaggregate the broad spatial structuring found in this national regression model.

Linear random intercept multilevel models were created using the 'lme4 1.1-9' [R] package, complemented by the 'lmerTest 2.0-29' package to obtain additional tests of significance. Finally, the 'MuMIn 1.15-1' package was implemented to derive Nakagawa and Schielzeth's (2013) method for obtaining R-Squared values from generalised linear mixed-effects models.

Geographically weighted regression (GWR)

Non-stationary relationships are likely to exist as a consequence of: (1) sampling variations within the data; (2) contextual issues that produce spatially differing responses to the same stimuli; and/or (3) model misspecification (Fotheringham *et al.,* 1998). Such datasets thus pose a significant dilemma for traditional regression models, which assume observations to be independent of one another. Hence the nature of a model must alter over space to reflect the structure within the data.

Rather than calibrating a single regression equation (Eq.1), GWR generates individual regression equations for each of the OSGB 10 km^2 cells, applying different weightings for the observations contained within the dataset (Fotheringham *et al.,* 1998):

$$\mathbf{y_i = \beta_0(u_i) + \beta_1(u_i)X_{i1} + \beta_2(u_i)X_{i2} + \ \dots\ \beta_N(u_i)X_{iN} + \varepsilon_i(u_i)}$$

(Eq.6)

Where $(\mathbf{u_i})$ represents the location of observation **i**, and thus $\boldsymbol{\beta_1}(\mathbf{u_i})$ indicates that the regression coefficient $\boldsymbol{\beta_1}$ defines a relationship specific to location **i**. The weight assigned to all other observations is based on a distance decay function, centred on the centroid of an OSGB 10 km^2 cell observation **i**. The calculation of the GWR model coefficients may be expressed as (Fotheringham *et al.,* 1998):

$$\boldsymbol{\beta}(\mathbf{u_i}) = (\mathbf{X^T\ W(u_i)\ X})^{-1}\ \mathbf{X^T\ W(u_i)\ y}$$

(Eq.7)

Where the superscript T denotes the transposition of a matrix, and $\mathbf{W(u_i)}$ is the weight to be applied to locality **i**, derived from a proximity based geographical weight matrix of locality **i** and its neighbouring elements $\mathbf{J_{1\dots N}}$. Through placing higher weightings based on proximity, GWR clearly adheres to the first law of geography, which states "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970, p236). Under this premise, sampling variations, issues of independence between observations, and response variations are addressed where suitable spatial weighting structures are devised.

Model weighting schemes were constructed from an adaptive decay function, defined by the consistent inclusion of 60, 50, or n nearest neighbour (NN) observations in each local model; observations separated by a distance greater than the bandwidth were allocated a weight of to zero. The bi-square weighting of observation **i** and its neighbour **j** can be expressed as a function of the distance **d** between localities and the applied bandwidth **b** (Fotheringham *et al.,* 2002):

$$\begin{aligned} \mathbf{W_{ij}} &= \left[\mathbf{1-\left(d_{ij}/b\right)^2}\right]^{\mathbf{2}} && \mathbf{if\ d_{ij} < b} \\ &= \mathbf{0} && \mathbf{if\ d_{ij} \geq b} \end{aligned}$$

(Eq.8)

GWR models were created using the 'spgwr 0.6-26' [R] package, with overall model validation achieved by conducting two ANOVA based generalised degrees of freedom F-tests, which differ by how their effective degrees of freedom are defined. The FBC-F derived by Fotheringham *et al.,* (2002) uses the effective degrees of freedom derived from the model's Residual Sum of Squares (RSS) to calculate an approximate likelihood ratio test to compare GWR and OLS model abilities of reproducing the original dataset. The F-value is obtained via the OLS-RSS/GWR-RSS ratio with (df1, df2) denoting the respective OLS and GWR models degrees of freedom.

$$\mathbf{OLS\ RSS} = (\mathbf{n} - \mathbf{k})\ \boldsymbol{\sigma}^2$$
$$\mathbf{GWR\ RSS} = (\mathbf{n} - [\mathbf{2tr}(\mathbf{S}) - \mathbf{tr}(\mathbf{S}^{\mathbf{T}}\mathbf{S})]\boldsymbol{\sigma}^2$$

(Eq.9)

The effective number of parameters in GWR is given by $\mathbf{2tr}(\mathbf{S}) - \mathbf{tr}(\mathbf{S}^{\mathbf{T}}\mathbf{S})$, where the hat matrix **S** describes the influence of each observed **y** on each fitted $\hat{\mathbf{y}}$ of the GWR model through the notation: $\hat{\mathbf{y}}$**=Sy**. The effective number of parameters in a GWR is often not an integer but varies between the traditionally defined number of parameters k (when the bandwidth tends to infinity) and n (when the bandwidth tends to zero). In many cases, **tr(S)** is very close to $\mathbf{tr(S^TS)}$ so an approximate value for the effective number of parameters is **tr(S)** (Fotheringham *et al.,* 2002).

Unlike the prior OLS and SEM strategies, GWR fully embraces the possibility of spatially divergent relationships that respond to a given influence across different locations, through the direct incorporation of spatial influence in parametrisation of the independent variables. The creation of coefficients unique to each location (spatially varying) enables one to explore the richness of the underlying data, identifying highly-localised relations which may have been smoothed away by 'global' modelling strategies (i.e. coefficients representative of national rates of change).

GWR initially established itself as a useful exploratory analytical tool, which if iterated over multiple weighting schemes, generates a series of location-specific parameter estimates. These estimates are useful in describing nonstationary spatial relationships across various scales of influence (i.e. local, regional, or sub-national responses). Under this premise, GWR is likened to a 'spatial microscope' observing variations in parameter surfaces across different levels of smoothing. Openshaw (1984) outlines that caution should be taken when interpreting zonal objects, with magnitudes of spatial deviation between predictor and response having the potential to differ wildly in accordance to the scale and pattern of the areal units modelled; a phenomenon known as the Modifiable Areal Unit Problem (MAUP). With GWR, there may be similar questions about the resolution, and therefore the detail, of the spatial interactions that one would wish to capture. Issues around selecting an optimum GWR spatial weighting scheme have since been addressed through the development of statistically appropriate measures, later compiled into a formal testing procedure by Jephcote *et al.,* (2014) to minimise concerns of modelling uncertainty.

GWR provides a useful description of localised stimulus-response relations at a given moment in time, potentially offering a near-perfect fit to the training data. However, GWR models are not suitable for predicting future scenarios or providing in-depth measures of model uncertainty, which may only be achieved through complex, spatially varying approaches conducted under a Bayesian framework with viable, prior probability distributions.

7.2 Results

7.2.1 Exploratory spatial data analysis (ESDA)

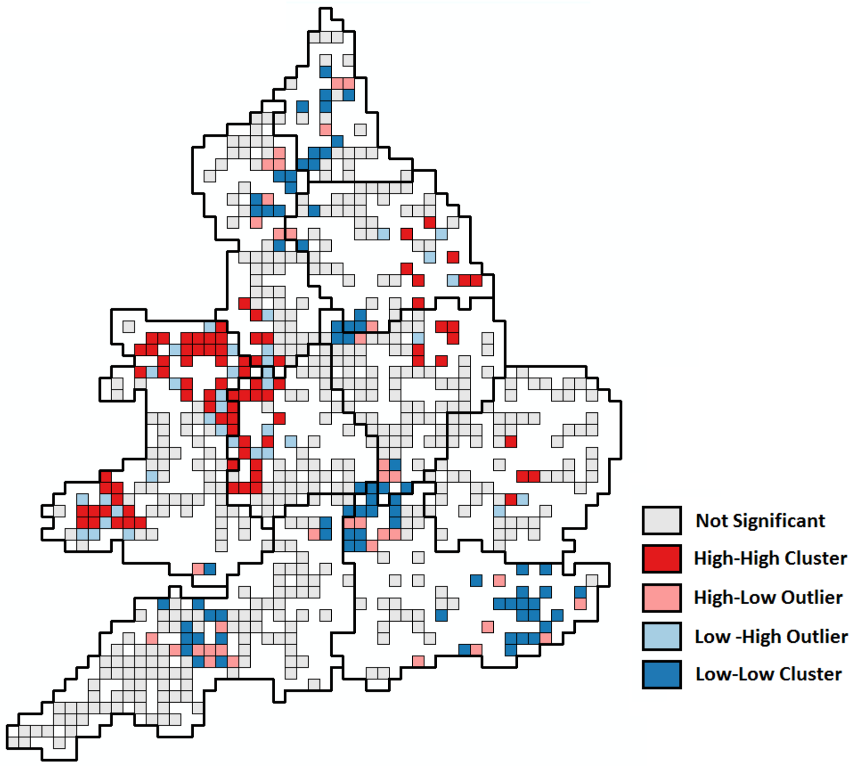
Figure 7-1 presents the Local Moran's I (Anselin, 1995) output for rates of agricultural land rental, under a row standardised fixed distance band weighting scheme of 50 km, which provides a visual analysis at the sub-regional scale. A significant yet mild element of spatial autocorrelation was observed at a national level (0.10, P≤0.01), although it is hard to detect the true extent of autocorrelation where the spatial positioning of gridded datasets are generally fragmented.

The presence of spatial autocorrelation can inflate Type I errors (false positive) in statistical analyses, creating a ‘red herring’ in the interpretation of partial regression coefficients to the extent that virtually all past ecological framework analyses are flawed (Lennon, 2000). Diniz-Filho *et al.,*’s (2003) comparison of OLS and spatially structured generalised least squares models concluded that “although spatial autocorrelation should always be investigated, it does not necessarily generate bias. Rather, it can be a useful tool to investigate mechanisms operating on richness at different spatial scales”. Still, it is likely that factors wrongly described as important constitute a ‘red-shifted’ subset of the set of potential explanations (autocorrelation often coinciding with the explanatory), and more spatially discontinuous factors are actually relatively more important than their present status suggests (Diniz-Filho *et al.,* 2003; Lennon 2000). Table 7-1 demonstrates that although only a mild element of spatial autocorrelation nationally exists in agricultural rental rates, clear localised variations are present which should be considered.

A visual inspection of local spatial elements reveals multiple high outlying (H-L) grid cells within the vicinity of rental value cold-spots (L-L), across a north-easterly stretch of land bounded by the Lake District and Yorkshire Dales. These relatively high LOG_{10} rental rates at a sub-regional level range from 2.2 to 2.4, and are neighboured by cells with low rental values (1.7 to 2.1) typically below the 2012 national average of 2.2.

A minor cluster of high land values (H-H) is found to encircle Lincoln recording LOG_{10} rental rates of 2.3, with further spots of elevated rent occurring to the north around Hull and York (2.2 to 2.6). A third small hot-spot (H-H) falls between Cambridge, Ipswich and Colchester where LOG_{10} rental rates are found to peak at 2.5. The most prominent areas of high rent are to be found along the Welsh border extending from Hereford up to Telford and Shrewsbury (2.2 to 2.5), around Snowdonia National Park (2.2 to 2.6) and thirdly in Pembrokeshire (2.3 to 2.8).

Areas with low agricultural rental values (L-L) are found around the south-eastern towns of Maidstone and Tunbridge Wells (1.8 to 2.0), as well as Hastings and Eastbourne (1.9 to 2.1). Here, the occasional High-Low (H- L) outlying land cell can be found close to Brighton and Uckfield (2.3). Similarly, a large cold-spot exists throughout the South-Midlands (1.8 to 2.0) with the odd high outlying land cell (H-L) located around the major urban centres of Northampton (2.2 to 2.5) and Oxford (2.3 to 2.4). Common areas of low land value (L-L) reappear around the Somerset-Devon border (1.8 to 2.1), with a patch of High-Low (H-L) outliers found between Exeter and Taunton (2.2 to 2.5).



Category	Autocorrelation	Z-Score Interpretation
High-High (H:H)	Positive	A high value feature neighboured by equally high value features
High-Low (H:L)	Negative	A high value feature (outlier) neighboured by low value features
Low-Low (L:L)	Positive	A low value feature neighboured by equally low value features
Low-High (L:H)	Negative	A low value feature (outlier) neighboured by high value features

Figure 7-1 Local Moran's I output for rates of agricultural land rental (£/ha) in 2012, under a row-standardised fixed distance band weighting scheme of 50 km (P≤0.05)

7.2.2 Spatial regression: national model

As previously discussed, the dependent variable was given a LOG_{10} transformation to create an input and output (regression residuals) dataset with a normal distribution. In a traditional regression model constructed from untransformed data, the contribution of an independent (**X**) variable is found by multiplying the variables observed value (**X_N**) by its respective regression coefficient (**β_N**); here, the expected value can be thought of as the arithmetic mean. In contrast, for a model where the dependent variable is in a transformed state, and the independent variables are in their original metric, coefficients other than the intercept are routinely interpreted in terms of a percentage change on the dependent variable.

Here, the intercept (starting or base value in rent) may be obtained through the inverse of the natural-logarithmic function, which for the following models is achieved via: **$10^\wedge(\beta_0)$.** This gives an expected value of rent in £/ha, where all other independent (**X**) variables are equal to zero. The interpretation format for physically measured dependent variables, are described by **$([10^{(X_N*\beta_N)} - 1] * 100)$** changes in the percentage of the dependent (**Y**) variable for a measured-unit increase in the independent (X) variable, where all other model variables are held constant. These values correspond to self-contained changes in the ratio of the expected geometric means of the dependent variable (i.e. a theoretical situation where no other influences on land rent are assumed to exist, so the interactions between dependent variables are not considered).

Prior to the application of multivariate methods, the independent (**X**) variables went through a process known as Grand Mean Centring (GMC). This involves the subtraction of a variable's average from each observation point. Through this approach, the slope between predictor and response remains unchanged, but the interpretation of the intercept (response when $\mathbf{X_{1\text{-}N} = 0}$) defines the mean rental value. The intercept now has meaning when working with a LOG_{10} transformed outcome, where independent variables that are measured are described as a percentage change on the geometric mean of the dependent (**Y**) variable as represented by the intercept.

Ordinary least squares (OLS)

OLS regression models examined the effects of nine explanatory agro-economic variables on agricultural land rental values in 2012. While representing a relatively poor goodness-of-fit to the dependent data (R^2=0.05), the ANOVA F-test significant at the 5% level suggests that an acceptable list of independent variables are present. This can be further explored by techniques that can account for unknown elements of spatial variability (Table 7-5). Significant clustering amongst OLS model residuals (Moran's I $P<0.01$) in conjunction with the knowledge of localised rent patterns, reinforce the need for modelling approaches to account for the dataset's spatial nature. The presence of spatial autocorrelation within the residuals is considered a violation of standard statistical techniques that assume independence among observations (Ibeas *et al.,* 2012; Longley and Tobon 2004).

While providing a relatively poor goodness-of-fit, the OLS Model did identify statistically significant underlying trends in the data at the 5% significance level (Figure 7-3):

- After removing the influence of agro-economic factors, the average baseline (intercept) price of rent across England and Wales equates to £159.95 (95% CI: 153.81 - 166.34) per ha.
- An inverse relationship exists between land rental price and the classification of land quality, where Grade 1 is deemed to be of 'excellent quality' and Grade 5 is 'very poor land restricted to permanent pasture'
- A positive relationship exists between land rental price and the average distance from an urban area (km) that a 10 km^2 OSGB land parcel is logarithmically (Base 10) situated.

Under an OLS modelling scheme, proximity to, or the interactions of specific AD plants, were not observed to have a significant national level of influence on agricultural land rental prices Table 7-3 provides a summary of the OLS models estimated change in rental rates (%) associated with a percentile unit shift in an independent variable away from its median (50^{th} percentile) value. In other words, it is measuring how the influence on rent, at various points in an independent variable's distribution, differs from the influence of the said variable at its most likely value. Table 7-3 B summarises these outputs in a monetary form for those independent variables identified to have a significant influence on rent under an OLS modelling framework.

Table 7-3 OLS estimated % change on baseline (model Intercept) agricultural rental values, associated with a percentile unit shift in an independent variable away from its median (50th Percentile) value. Here, the 25th percentile category is representative of the change in rent (%) on agricultural land valued at £159.96 per ha, associated with the observed difference between the median (expected influence) and 25% lowest values of an independent variable.

	% change in rental values associated with the difference between the Nth percentile and the median value of an independent variable (95% confidence interval)			
	1st Percentile	25th Percentile	75th Percentile	99th Percentile
(X1) Land Covered by FAT Agreements (%)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	-1.25 (-2.7, 0.21)	-9.24 (-18.98, 1.66)
(X2) Agricultural Land Classification (ALC)	26.52 (9.78, 45.82)	2.86 (1.13, 4.64)	-6.74 (-10.6, -2.73)	-20.11 (-30.23, -8.52)
(X3) LOG_{10} "Motorway Proximity" (km)	-2.95 (-14.27, 9.86)	-0.86 (-4.36, 2.76)	0.76 (-2.37, 4)	2.26 (-6.78, 12.19)
(X4) LOG_{10} "Urban Proximity + 1" (km)	-10.65 (-20.09, -0.11)	-3.42 (-6.69, -0.03)	4.13 (0.04, 8.40)	11.51 (0.11, 24.22)
(X5) Carstair's Deprivation Index (z-score)	-5.53 (-10.98, 0.25)	-2.34 (-4.73, 0.1)	3.02 (-0.13, 6.28)	11.01 (-0.46, 23.81)
(X6) Maize Coverage (ha)	-0.58 (-1.74, 0.59)	-0.51 (-1.54, 0.52)	1.37 (-1.36, 4.19)	8.86 (-8.14, 29.03)
(X7) Agricultural Land Suited for Maize (%)	-0.57 (-3.01, 1.93)	-0.57 (-3.01, 1.93)	1.48 (-4.83, 8.23)	2.58 (-8.19, 14.62)
(X8) LOG_{10} "AD Plant Proximity" (km)	4.72 (-7.06, 18.00)	1.18 (-1.84, 4.30)	-1.15 (-4.09, 1.86)	-3.53 (-12.11, 5.88)
(X8-INT A) Nearest AD Plant Output (kWe)	0.24 (-3.84, 4.50)	0.19 (-3.13, 3.63)	-0.18 (-3.29, 3.02)	-0.74 (-12.78, 12.95)
(X8-INT B) Influence of "Crop" Fed AD Plants (%)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	-1.34 (-13.95, 13.11)
(X8) : (X8-INT A)	1.09 (-10.19, 13.80)	0.21 (-2.14, 2.64)	0.14 (-1.46, 1.78)	2.20 (-19.33, 29.49)
(X8) : (X8-INT B)	-2.50 (-9.36, 4.86)	-0.64 (-2.47, 1.21)	0.64 (-1.19, 2.51)	-9.20 (-31.16, 19.75)
(X8-INT A) : (X8-INT B)	0.31 (-1.33, 2.00)	0.25 (-1.08, 1.61)	-0.24 (-1.49, 1.02)	4.36 (-16.53, 30.48)
(X8) : (X8-INT A) : (X8-INT B)	-2.19 (-7.92, 3.87)	-0.44 (-1.65, 0.77)	-0.30 (-1.12, 0.52)	23.14 (-29.96, 116.52)

Table 7-3B: Significant OLS estimated changes (£/ha) in rental values on agricultural land valued at £159.96 per ha, associated with a percentile unit shift on an independent variable away from its median (50th percentile) value.

	Change in rental value (£/ha) associated with the difference between the Nth percentile and the median value of an independent variable (95% confidence interval)			
	1st Percentile	**25th Percentile**	**75th Percentile**	**99th Percentile**
(X1) Land Covered by FAT Agreements (%)	--	--	-2.01	-14.78
(X2) Agricultural Land Classification (ALC)	+42.43	+4.59	-10.80	-32.17
(X4) LOG_{10} "Urban Proximity + 1" (km)	-17.05	-5.47	+6.62	+18.42
(X5) Carstair's Deprivation Index (z-score)	-8.85	-3.75	+4.84	+17.62

Green Cells = Significant at the 0.05 level, White Cells = Correlation significant at the 0.10 level

The highest quality agricultural land (1st percentile ALC = 1.43) was shown to command an additional £42.43 per ha on expected land rental prices, with the poorest quality land (99th percentile ALC = 4.86) resulting in a £32.17 decrease in rent per ha (Table 7-3 B). Agricultural land most distant from urban centres (99th percentile proximity = 34.39 km) was shown to command an additional £18.42 per ha on expected land rental prices, with farmed land close to urban locations (1st percentile proximity = 0.02 km) having a rental price of £17.05 per ha beneath the expected value (Table 7-3 B). We can speculate that lower rental values close to urban areas may be because of perceived risk of damage to crops, or interference with field operations, through the activities of the local population. For example, complaints about spraying pesticides may be greater, or there may be damage to crops by people walking through fields.

Spatial error model (SEM)

Following the detection of spatial correlation in the residuals of the conventional multivariate regression, a series of spatial error models were constructed to provide national estimates while accommodating for these geographic trends. Under this framework spatial dependence is treated as a nuisance and enters the model through the error component, the outputs of which highlight the locations of spatial anomalies and have the potential to inform future models. The separation out of observed yet unknown spatially varying processes to the error component, allows for a geographically adjusted test of significance for processes known a-priori. The most significant term in this type of regression model purposely falls within the error component.

Spatial structures used to capture the spatial error component were defined by weighting neighbouring observations under row-standardised spatial continuity schemes, across 20 km increments. For instance, under a 100 km continuity scheme, a pair of OSGB 10 km^2 grid cells are only considered to have some form of relation (neighbouring) if their centroids are not separated by a Euclidean distance of more than 100 km. On average, 109.7 links (neighbouring pairs) existed at each OSGB 10 km^2 grid cell for a 100 km continuity scheme, the individual influence of which were row-standardised by neighbour count, to prevent any individual areal unit from having an overshadowing influence.

Table 7-5 summarises the OLS and Spatial Error Model (SEM) outputs in quantifying how agro-economic factors affect logarithmically-transformed agricultural land rental prices (£/ha). Figure 7-2 displays mapped outputs of the various employed neighbourhood continuity schemes, alongside the geographic distribution of the SEM residual components.

A slight improvement on OLS model performance was observed in the SEMs, which provided pseudo R-squared (Nagelkerke, 1991) values of 0.12 to 0.14 when using a 100 to 40 km continuity scheme. This shows that the preceding OLS model had diminished the influence of predictive variables in defining national agricultural rental trends. However, the low pseudo R-squared value of the SEM would imply that spatial elements (contained in the residuals) have prominent influence. The two sample Kolmogorov-Smirnov test is a nonparametric test which compares the cumulative distributions of the residual dataset to a normal distribution in which the null hypothesis ($P>0.05$) confirms if sampling has occurred across identical distributions. The OLS and all SEM schemes indicate normality within the residuals, a key indicator of acceptable model performance.

In general, the accepted way of choosing between fixed and random effects is through running a Hausman test. Random effects (spatial error component) often allow for a more efficient estimator and will provide better P-values. However, these should only exist where statistically justifiable. The null hypothesis of the Hausman test states that the coefficients estimated by the efficient random effects estimator are the same as the ones estimated by the consistent fixed effects estimator. If they are insignificant (P-Value >0.05) it is safe to use random effects. Table 7-4 shows the underlying spatial continuity scheme for each SEM to be satisfactory. Further validation of the spatial component in the SEMs was achieved via the Likelihood Ratio (LR) test, which universally indicates model performance to have improved through the inclusion of a spatial error component (P-Value <0.01). Finally, the null hypothesis of the Wald Statistic test states that a set of parameters with or without the spatial component are equal to some value. Tests on all SEM models reject the Wald Statistic null hypothesis (P-Value <0.01), suggesting that removal of the spatial component would detrimentally impact the overall model fit. Still, the low probability in the Breusch-Pagan test corrected for the spatial coefficient lambda), would suggest the presence of heteroskedasticity (observations with substantially different error variance), indicating that highly-localised spatial influences remain unaccounted for.

An SEM with a neighbourhood continuity scheme of 80km was identified to have an optimum balance between model fit (R-squared) and significant global correlation in the residuals (Moran's):

- After removing the influence of agro-economic factors, the average baseline (intercept) price of rent across England and Wales equates to £163.49 (95% CI: 138.47 - 193.05) per ha.
- An inverse relationship exists between land rental price and the classification of land quality, where Grade 1 is deemed to be of 'excellent quality' and Grade 5 is 'very poor land restricted to permanent pasture.
- An inverse relationship exists between land rental prices and the uptake of FAT tenancies. This perhaps reflects the stable income that a long-term agreement can provide.

Under various SEM schemes, proximity to any or the interactions of specific AD plants, were not observed to have a significant national level of influence on agricultural land rental prices. Table 7-5 Table 7-4presents a summary of the SEM 80 km scheme model's estimated changes in rental prices (%) associated with a percentile unit shift in an independent variable away from its median (50^{th} percentile) value. Table 7-5 summarises these outputs in a monetary form, for those independent variables identified to have a significant influence on land rental price under an OLS modelling framework.

Table 7-4 SEM 80 km scheme estimated % change on baseline (Model Intercept) agricultural rental rates, associated with a percentile unit shift in an independent variable away from its median (50th Percentile) value. Here, the 25th percentile category is representative of the change in rent (%) on agricultural land valued at £163.49 per ha, associated with the observed difference between the median (expected) and 25% lowest values of an independent variable.

	% change in rental rates associated with the difference between the Nth percentile and the median value of an independent variable (95% confidence interval)			
	1st Percentile	**25th Percentile**	**75th Percentile**	**99th Percentile**
(X1) Land Covered by FAT Agreements (%)	**0.00 (0.00, 0.00)**	**0.00 (0.00, 0.00)**	**-1.65 (-3.01, -0.27)**	**-12.01 (-20.93, -2.08)**
(X2) Agricultural Land Classification (ALC)	**37.06 (17.58, 59.78)**	**3.86 (1.97, 5.79)**	**-8.93 (-12.99, -4.7)**	**-25.98 (-36.07, -14.32)**
(X3) LOG "Motorway Proximity" (km)	**4.72 (20.48, -8.97)**	**1.34 (-2.69, 5.54)**	**-1.16 (-4.64, 2.43)**	**-3.38 (-12.99, 7.27)**
(X4) LOG "Urban Proximity + 1" (km)	**-1.98 (-12.53, 9.84)**	**-0.61 (-4.05, 2.94)**	**0.72 (-3.32, 4.93)**	**1.95 (-8.67, 13.82)**
(X5) Carstair's Deprivation Index (z-score)	**0.15 (-5.63, 6.30)**	**0.06 (-2.39, 2.58)**	**-0.08 (-3.15, 3.08)**	**-0.28 (-10.61, 11.23)**
(X6) Maize Coverage (ha)	**-0.82 (-2.13, 0.49)**	**-0.73 (-1.88, 0.44)**	**1.96 (-1.14, 5.16)**	**12.8 (-6.89, 36.66)**
(X7) Agricultural Land Suited for Maize (%)	**-2.41 (-5.19, 0.44)**	**-2.41 (-5.19, 0.44)**	**6.52 (-1.12, 14.76)**	**11.52 (-1.93, 26.82)**
(X8) LOG "AD Plant Proximity" (km)	**-3.23 (-15.25, 10.49)**	**-0.83 (-4.12, 2.57)**	**0.83 (-2.48, 4.26)**	**2.59 (-7.49, 13.78)**
(X8-INT A) Nearest AD Plant Output (kWe)	**-2.21 (-6.9, 2.72)**	**-1.79 (-5.63, 2.20)**	**1.71 (-2.01, 5.58)**	**7.18 (-7.99, 24.87)**
(X8-INT B) Influence of "Crop" Fed AD Plants (%)	**0.00 (0.00, 0.00)**	**0.00 (0.00, 0.00)**	**0.00 (0.00, 0.00)**	**-2.79 (-16.36, 12.98)**
(X8) : (X8-INT A)	**4.36 (-7.99, 18.38)**	**0.86 (-1.67, 3.46)**	**0.58 (-1.13, 2.33)**	**8.91 (-15.35, 40.12)**
(X8) : (X8-INT B)	**-1.22 (-7.76, 5.76)**	**-0.31 (-2.03, 1.43)**	**0.31 (-1.4, 2.06)**	**-4.59 (-26.44, 23.74)**
(X8-INT A) : (X8-INT B)	**0.03 (-1.84, 1.95)**	**0.02 (-1.5, 1.58)**	**-0.02 (-1.45, 1.42)**	**0.46 (-22.16, 29.67)**
(X8) : (X8-INT A) : (X8-INT B)	**-0.60 (-6.21, 5.34)**	**-0.12 (-1.28, 1.05)**	**-0.08 (-0.87, 0.71)**	**5.82 (-38.55, 82.25)**

Table 7-4 B: Significant SEM estimated changes (£/ha) in rental price on agricultural land valued at £163.49 per ha, associated with a percentile unit shift on an independent variable away from its median (50th percentile) value.

	Change in rental price (£/ha) associated with the difference between the Nth percentile and the median value of an independent variable (95% confidence interval)			
	1st Percentile	**25th Percentile**	**75th Percentile**	**99th Percentile**
(X1) Land Covered by FAT Agreements (%)	--	--	-2.70	-19.63
(X2) Agricultural Land Classification (ALC)	60.60	6.31	-14.62	-42.49
(X7) Agricultural Land Suited for Maize (%)	-3.95	-3.95	10.66	18.84

Green Cells = Significant at the 0.05 level, White Cells = Correlation significant at the 0.10 level

Prices of rent tend to decrease where a higher proportion of a 10 km^2 land parcel is farmed under FAT agreements, with the expected price of rent per ha decreasing by £19.63 where all land is under a FAT agreement (Table 7-4 B). The highest quality agricultural land (1st percentile ALC = 1.43) was shown to command an additional £60.60 per ha on expected land rental prices, with the poorest quality land (99th percentile ALC = 4.86) resulting in a £42.49 decrease in rent per ha (Table 7-4 B).

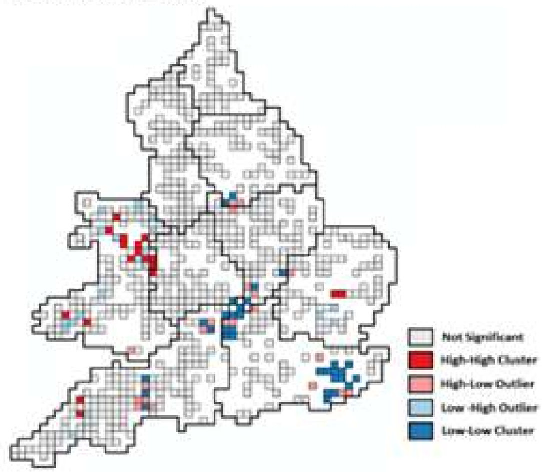
Table 7-5 OLS and Spatial Error Model (SEM) outputs quantifying agro-economic influences on LOG_{10} transformed agricultural land rental prices (£/ha). Structures of spatial error defined by weighting neighbouring observations under row-standardised spatial continuity schemes of 20 to 100 km.

	OLS			SEM 100 km Neighbourhood Continuity			SEM 80 km Neighbourhood Continuity		
	β Value	Std. Error	P-Value	β Value	Std. Error	P-Value	β Value	Std. Error	P-Value
(X0) Intercept	2.20E+00	8.66E-03	0.000	2.22E+00	5.44E-02	0.000	2.21E+00	3.68E-02	0.000
(X1) Land Covered by FAT Agreements (%)	-4.21E-04	2.51E-04	0.094	-4.99E-04	2.38E-04	0.036	-5.56E-04	2.37E-04	0.019
(X2) Agricultural Land Classification (ALC)	-5.13E-02	1.58E-02	0.001	-7.24E-02	1.65E-02	0.000	-6.88E-02	1.70E-02	0.000
(X3) LOG "Motorway Proximity" (km)	1.07E-02	2.26E-02	0.635	-5.37E-03	2.50E-02	0.830	-1.65E-02	2.56E-02	0.518
(X4) LOG "Urban Proximity + 1" (km)	6.27E-02	3.16E-02	0.048	9.45E-03	3.21E-02	0.769	1.11E-02	3.22E-02	0.730
(X5) Carstair's Deprivation Index (z-score)	6.90E-03	3.67E-03	0.061	-1.28E-03	3.67E-03	0.728	-1.87E-04	3.68E-03	0.959
(X6) Maize Coverage (ha)	4.15E-05	4.23E-05	0.326	5.73E-05	4.67E-05	0.220	5.89E-05	4.77E-05	0.218
(X7) Agricultural Land Suited for Maize (%)	1.36E-04	3.01E-04	0.652	5.27E-04	3.41E-04	0.122	5.80E-04	3.48E-04	0.096
(X8) LOG "AD Plant Proximity" (km)	-2.44E-02	3.21E-02	0.448	7.06E-03	3.39E-02	0.835	1.73E-02	3.57E-02	0.627
(X8-INT A) Nearest AD Plant Output (KWe)	-2.11E-06	1.85E-05	0.910	2.74E-05	2.15E-05	0.204	1.95E-05	2.19E-05	0.372
(X8-INT B) Influence of "Crop" Fed AD Plants (%)	-5.88E-05	3.02E-04	0.846	-7.77E-05	3.11E-04	0.803	-1.23E-04	3.33E-04	0.712
(X8) : (X8-INT A)	9.87E-06	5.46E-05	0.857	3.65E-05	5.79E-05	0.529	3.87E-05	5.81E-05	0.506
(X8) : (X8-INT B)	-7.64E-04	1.12E-03	0.494	-9.04E-04	1.05E-03	0.390	-3.72E-04	1.05E-03	0.723
(X8-INT A) : (X8-INT B)	1.58E-07	4.21E-07	0.708	-1.51E-07	4.52E-07	0.738	1.72E-08	4.81E-07	0.971
(X8) : (X8-INT A) : (X8-INT B)	1.15E-06	1.58E-06	0.469	5.78E-07	1.53E-06	0.706	3.12E-07	1.52E-06	0.838
A. Model Performance									
Pseudo R-squared (Nagelkerke, 1991)	0.05			0.12			0.13		
AIC	-219.62			-259.52			-266.21		
Log-Likelihood	125.81			146.76			150.10		
Kolmogorov–Smirnov Residual test	0.04 (P-Value: 0.18)			0.04 (P-Value: 0.26)			0.04 (P-Value: 0.20)		
Moran's I Residual test	0.10 (P-Value: <0.01)			0.03 (P-Value: <0.01)			0.02 (P-Value: 0.02)		
F-Test	2.27 (P-Value: <0.01)			--			--		
B. Spatial Component Validation									
Lambda	--			0.86			0.80		
Likelihood Ratio (LR) Test	--			45.41 (P-Value: <0.01)			48.59 (P-Value: <0.01)		
Asymptotic Standard Error	--			0.06 (P-Value: <0.01)			0.07 (P-Value: <0.01)		
Wald Statistic	--			86.82 (P-Value: <0.01)			128.14 (P-Value: <0.01)		
Spatial Hausman Test	--			13.71 (P-Value: 0.55)			14.74 (P-Value: 0.47)		
Breusch-Pagan Test	--			28.30 (P-Value: 0.01)			28.15 (P-Value: 0.01)		

	SEM 60 km Neighbourhood			SEM 40 km Neighbourhood			SEM 2 0km Neighbourhood		
	β Value	**Std. Error**	**P-**	**β Value**	**Std. Error**	**P-Value**	**β Value**	**Std. Error**	**P-Value**
(X0) Intercept	2.21E+00	2.46E-02	0.000	2.21E+00	1.75E-02	0.000	2.21E+00	1.08E-02	0.000
(X1) Land Covered by FAT Agreements (%)	-6.05E-04	2.37E-04	0.011	-5.72E-04	2.34E-04	0.014	-5.16E-04	2.40E-04	0.032
(X2) Agricultural Land Classification (ALC)	-6.41E-02	1.73E-02	0.000	-5.83E-02	1.78E-02	0.001	-5.15E-02	1.74E-02	0.003
(X3) LOG "Motorway Proximity" (km)	-2.72E-02	2.64E-02	0.303	-2.41E-02	2.77E-02	0.383	1.08E-02	2.55E-02	0.673
(X4) LOG "Urban Proximity + 1" (km)	1.41E-02	3.29E-02	0.669	2.44E-02	3.35E-02	0.465	4.80E-02	3.36E-02	0.153
(X5) Carstair's Deprivation Index (z-score)	3.90E-04	3.71E-03	0.916	9.06E-04	3.73E-03	0.808	4.30E-03	3.75E-03	0.252
(X6) Maize Coverage (ha)	6.19E-05	4.90E-05	0.207	4.61E-05	4.94E-05	0.351	4.08E-05	4.68E-05	0.383
(X7) Agricultural Land Suited for Maize (%)	5.01E-04	3.53E-04	0.155	2.94E-04	3.57E-04	0.410	1.83E-04	3.36E-04	0.587
(X8) LOG "AD Plant Proximity" (km)	2.73E-02	3.74E-02	0.465	3.94E-03	3.97E-02	0.921	-1.39E-02	3.73E-02	0.709
(X8-INT A) Nearest AD Plant Output (KWe)	1.54E-05	2.27E-05	0.495	1.08E-05	2.37E-05	0.649	4.37E-06	2.12E-05	0.837
(X8-INT B) Influence of "Crop" Fed AD Plants (%)	-1.51E-04	3.50E-04	0.665	-2.86E-04	3.70E-04	0.439	-1.45E-04	3.40E-04	0.670
(X8) : (X8-INT A)	5.94E-05	5.76E-05	0.302	5.17E-05	5.99E-05	0.388	2.83E-05	6.09E-05	0.642
(X8) : (X8-INT B)	-4.52E-04	1.07E-03	0.673	-8.34E-04	1.14E-03	0.464	-8.97E-04	1.21E-03	0.460
(X8-INT A) : (X8-INT B)	1.70E-07	5.03E-07	0.736	3.86E-07	5.13E-07	0.452	9.51E-08	4.74E-07	0.841
(X8) : (X8-INT A) : (X8-INT B)	6.42E-07	1.55E-06	0.679	1.36E-06	1.60E-06	0.396	1.31E-06	1.73E-06	0.447
A. Model Performance									
Pseudo R-squared (Nagelkerke, 1991)	0.13			0.14			0.09		
AIC	-263.03			-267.49			-240.97		
Log-Likelihood	148.52			150.75			137.48		
Kolmogorov–Smirnov Residual test	0.04 (P-Value: 0.28)			0.04 (P-Value: 0.14)			0.04 (P-Value: 0.22)		
Moran's I Residual test	0.01 (P-Value: 0.12)			0.01 (P-Value: 0.16)			0.05 (P-Value: <0.01)		
F-Test	--			--			--		
B. Spatial Component Validation									
Lambda	0.70			0.56			0.25		
Likelihood Ratio (LR) Test	45.41 (P-Value: <0.01			49.88 (P-Value: <0.01)			23.35 (P-Value: <0.01)		
Asymptotic Standard Error	0.07 (P-Value: <0.01			0.07 (P-Value: <0.01)			0.05 (P-Value: <0.01)		
Wald Statistic	86.82 (P-Value: <0.01)			71.24 (P-Value: <0.01)			23.40 (P-Value: <0.01)		
Spatial Hausman Test	16.15 (P-Value: 0.37)			18.38 (P-Value: 0.24)			16.02 (P-Value: 0.38)		
Breusch-Pagan Test	28.37 P-Value: 0.01)			29.07 (P-Value: 0.01)			29.70 (P-Value: 0.01)		

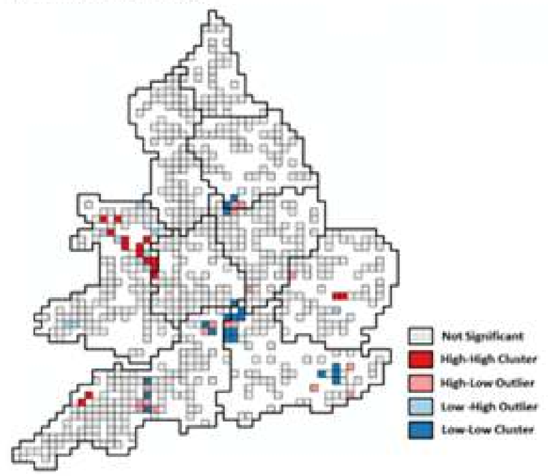
100 KM Neighbourhood Contiguity Scheme
[Average Link Count: 109.7]

Local Moran's I: 100 KM Spatial Error Model (SEM) Residuals
(I = 0.03, P-Value = 0.02)



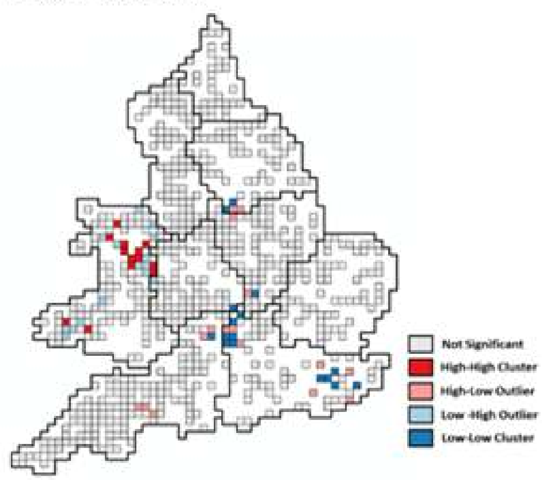
80 KM Neighbourhood Contiguity Scheme
[Average Link Count: 72.6]

Local Moran's I: 80 KM Spatial Error Model (SEM) Residuals
(I = 0.02, P-Value = 0.01)



60 KM Neighbourhood Contiguity Scheme
[Average Link Count: 44.8]

Local Moran's I: 60 KM Spatial Error Model (SEM) Residuals
(I = 0.01, P-Value = 0.12)



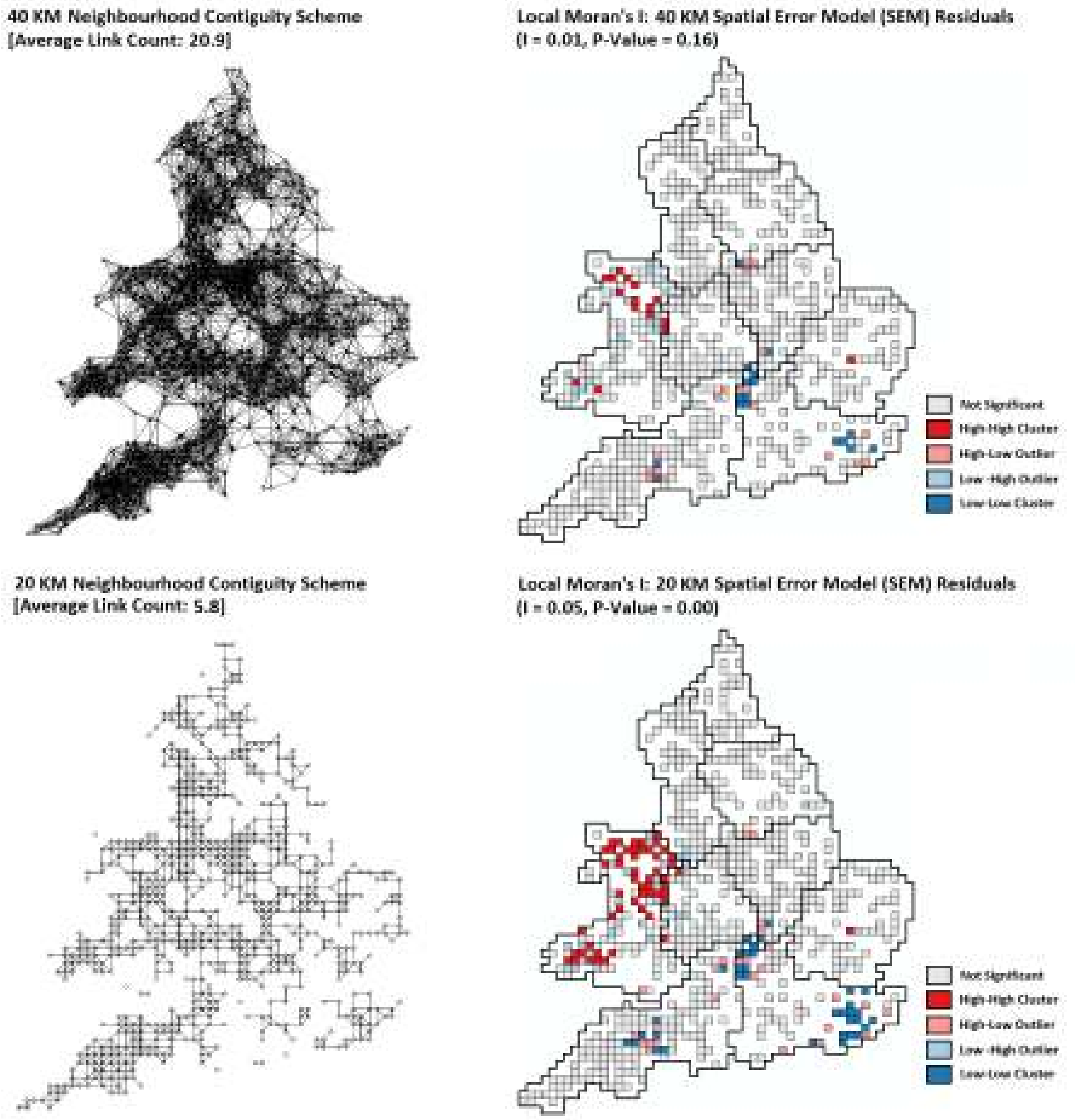


Figure 7-2 Spatial Error Model (SEM) neighbourhood association links (left) and Local Moran's I outputs for model residuals (right) under a row-standardised fixed distance band weighting scheme of 50 km (P≤0.05)

Multilevel modelling

A second spatial modelling, seeking to provide fixed parameter estimates representative of the national average response, was achieved through multilevel approaches. Regional and localised (residual feedback from the 80 km SEM) structures were used to broadly represent geographic elements within the dataset. OSGB 10 km^2 grid cells were then nested in these structures based on their spatial association; satisfying a requirement for independence between observations.

Table 7-8 provides a summary of linear random intercept multilevel model performance and outlines how fixed coefficient agro-economic factors sway LOG_{10} transformed agricultural land rental prices (£/ha) at a national level. Table 7-7 provides the intercept values for the hierarchical sources of variability.

Table 7-6 Random Intercept Multilevel Model outputs quantifying agro-economic influences on LOG_{10} transformed Agricultural land rental prices (£/ha). Spatial structures defined by regional distinction and the 80 km Spatial Error Model (SEM) residual classification (description of local spatial elements) provided in Figure 7-2

	Model A: Two-Tier Random Intercept (L2: Regional Intercept)			**Model B: Two-Tier Random Intercept (L2: Sub-Regional)**		
	β Value	**Std. Error**	**P-Value**	**β Value**	**Std. Error**	**P-Value**
(X0) Intercept	2.20E+00	2.29E-02	0.000	2.20E+00	2.64E-02	0.000
(X1) Land Covered by FAT Agreements (%)	-5.98E-04	2.39E-04	0.013	-6.24E-04	2.35E-04	0.008
(X2) Agricultural Land Classification (ALC)	-7.34E-02	1.61E-02	0.000	-7.23E-02	1.58E-02	0.000
(X3) LOG "Motorway Proximity" (km)	1.75E-02	2.30E-02	0.447	2.27E-02	2.28E-02	0.320
(X4) LOG "Urban Proximity + 1" (km)	1.96E-02	3.05E-02	0.521	1.13E-02	3.00E-02	0.707
(X5) Carstair's Deprivation Index (z-score)	9.41E-04	3.60E-03	0.794	6.61E-04	3.53E-03	0.851
(X6) Maize Coverage (ha)	8.44E-05	4.49E-05	0.060	7.05E-05	4.42E-05	0.112
(X7) Agricultural Land Suited for Maize (%)	4.15E-04	3.28E-04	0.207	5.10E-04	3.30E-04	0.123
(X8) LOG "AD Plant Proximity" (km)	6.84E-03	3.18E-02	0.830	2.06E-03	3.15E-02	0.948
(X8-INT A) Nearest AD Plant Output (kWe)	-9.69E-06	1.97E-05	0.623	-6.05E-06	1.96E-05	0.758
(X8-INT B) Influence of "Crop" Fed AD Plants (%)	-2.76E-05	3.03E-04	0.928	-1.47E-05	3.01E-04	0.961
(X8) : (X8-INT A)	5.15E-06	5.30E-05	0.923	8.14E-06	5.30E-05	0.878
(X8) : (X8-INT B)	-1.00E-03	1.07E-03	0.348	-9.00E-04	1.05E-03	0.391
(X8-INT A) : (X8-INT B)	1.61E-07	4.27E-07	0.706	1.84E-07	4.27E-07	0.668
(X8) : (X8-INT A) : (X8-INT B)	1.60E-06	1.50E-06	0.286	1.60E-06	1.49E-06	0.283
A. Model Performance						
R-squared (Marginal)	0.09			0.09		
R-squared (Conditional)	0.18			0.30		
AIC	-264.10			277.20		
Log-Likelihood	149.10			156.60		
Kolmogorov–Smirnov Residual test						
Moran's I Residual test	0.01 (P-Value: 0.15)			0.02 (P-Value: 0.10)		
B. Random Intercept (Spatial) Validation						
Log-Likelihood	49.5 (P-Value: 0.01)			64.6 (P-Value: <0.01)		

Table 7-7 Multilevel Model outputs random intercept values based on regional and sub-regional (80 km Spatial Error Model residual classification) geographies

		Two-Tier Random Intercept	Three-Tier Random Intercept
Level 2: Region	East Midlands (N=80)	-7.45E-03	
	East of England (N=67)	-1.02E-02	
	North East (N=33)	-3.58E-02	
	North West (N=69)	3.74E-02	
	South East (N=67)	-1.02E-01	
	South West (N=133)	-5.37E-02	
	Wales (N=113)	1.22E-01	
	West Midlands (N=63)	1.97E-02	
	Yorkshire and The Humber (N=57)	3.01E-02	
Level 2 : Sub-Regional (80 km SEM Residual Informed)	High-High: East of England (N=2)		4.32E-02
	High-High: South West (N=2)		3.84E-02
	High-High: Wales (N=11)		1.65E-01
	High-High: West Midlands (N=1)		1.79E-02
	High-Low: East Midlands (N=2)		9.38E-02
	High-Low: East of England (N=1)		2.65E-02
	High-Low: South East (N=5)		5.00E-02
	High-Low: South West (N=7)		6.53E-02
	High-Low: Yorkshire & The Humber (N=2)		2.57E-02
	Low-High: East of England (N=1)		-7.19E-02
	Low-High: Wales (N=9)		-5.21E-02
	Low-Low: East Midlands (N=1)		1.05E-04
	Low-Low: South East (N=11		-1.93E-01
	Low-Low: South West (N=6)		-1.55E-01
	Low-Low: West Midlands (N=1)		-1.14E-02
	Low-Low: Yorkshire & The Humber (N=2)		-0.1
	Not Significant: East Midlands (N=77)		-1.70E-02
	Not Significant: East of England (N=63)		-1.41E-02
	Not Significant: North East (N=33)		-3.38E-02
	Not Significant: North West (N=69)		4.66E-02
	Not Significant: South East (N=51)		-9.81E-02
	Not Significant: South West (N=118)		-4.73E-02
	Not Significant: Wales (N=93)		1.45E-01
	Not Significant: West Midlands (N=61)		2.53E-02
	Not Significant: Yorkshire & The Humber (N=53)		4.59E-02

Initially, a two-tier random intercept model was constructed containing the full series of agro-economic influences measured at the OSGB 10 km^2 cell (level 1). The observations from this were hierarchically nested by region as quantified by a random intercept value (level 2). For this model, the average baseline (fixed intercept) value of rent across England and Wales equates to £158.49 (95% CI: 142.90 to 175.78) per ha. The structure of regional variation as defined by the random intercept is observed to be of significance (P<0.01). When the fixed and random intercepts are summated and reverse transformed, the baseline in rent is found to range from £125.39 (South East) to £209.75 (Wales) per ha. The inclusion of a regional hierarchy has improved the modelling of parameterised variables (marginal R-Squared of 0.09) compared to the OLS model, with both fixed and random (spatial) model components producing a conditional R-Squared value of 0.18. In addition, clear underlying trends were identified in the data (Table 7-6):

- An inverse relationship exists between land rental price and the classification of land quality at the 5% significance level, where Grade 1 is deemed to be of 'excellent quality' and Grade 5 is 'very poor land restricted to permanent pasture'.
- An inverse relationship exists between land rental prices and the uptake of FAT tenancies at the 5% significance level. This perhaps reflects the stable income that a long-term agreement can provide.
- A positive relationship exists between land rental prices and the growth of maize crops (ha) at the 10% significance level; a trend not previously identified by OLS or the SEM.

A second two-tier random intercept model was constructed to explore the same OSGB 10 km^2 agro-economic influences (level 1), using a sub-regional nesting structure (level 2) formed through the disaggregation of regions into spatial components based on the Local Moran's I classification of the 80 km SEM residuals (see Table 7-8). Feedback from the SEM is expected to show where highly-localised influences on rent occur, and improve how the multi-level model responds to such challenges. The random intercept coefficients from this sub-regional two-tier hierarchy are presented in Table 7-7, the overall structure of which is significant (P<0.01). The average baseline (fixed intercept) price of rent across England and Wales is measured at £194.47 (95% CI: 139.08 to 176.50) per ha, however several regional and sub-regional differences exist. When the fixed and random intercepts are summated and reverse transformed, the baseline in rent for Wales is found to range from £138.97 to £229.24 per ha. For the South East, land rental prices are found to range from £100.43 to £175.80 per ha. While there has been no improvement in the marginal R-Squared (fixed coefficient contribution), there has been an improvement in the capture of spatial influences resulting in a conditional R-Squared of 0.30. Clear underlying trends were identified for land quality and tenancy type at the 5% significance level (Table 7-8).

Table 7-8 Sub-regional multi-level model estimated % change on baseline (Model Intercept) agricultural rental rates, associated with a percentile unit shift in an independent variable away from its median (50th Percentile) value. Here, the 25th percentile category is representative of the change in rent (%) on agricultural land valued at £156.68 per ha, associated with the observed difference between the median (expected) and 25% lowest values of an independent variable.

	% change in rental rates associated with the difference between the Nth percentile and the median value of an independent variable (95% confidence interval)			
	1st Percentile	**25th Percentile**	**75th Percentile**	**99th Percentile**
(X1) Land Covered by FAT Agreements (%)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	-1.85 (-3.2, -0.49)	-13.39 (-22.11, -3.7)
(X2) Agricultural Land Classification (ALC)	39.31 (20.89, 60.54)	4.06 (2.31, 5.85)	-9.37 (-13.12, -5.48)	-27.12 (-36.36, -16.56)
(X3) LOG "Motorway Proximity" (km)	-6.13 (-17.16, 6.35)	-1.81 (-5.31, 1.80)	1.62 (-1.56, 4.91)	4.84 (-4.5, 15.09)
(X4) LOG "Urban Proximity + 1" (km)	-2.00 (-11.87, 8.96)	-0.62 (-3.83, 2.69)	0.73 (-3.04, 4.65)	1.98 (-7.96, 13.00)
(X5) Carstair's Deprivation Index (z-score)	-0.54 (-6.06, 5.30)	-0.22 (-2.57, 2.18)	0.28 (-2.67, 3.33)	1.00 (-9.04, 12.17)
(X6) Maize Coverage (ha)	-0.98 (-2.19, 0.23)	-0.87 (-1.94, 0.20)	2.35 (-0.54, 5.32)	15.50 (-3.3, 37.97)
(X7) Agricultural Land Suited for Maize (%)	-2.12 (-4.77, 0.59)	-2.12 (-4.77, 0.59)	5.70 (-1.50, 13.44)	10.05 (-2.57, 24.32)
(X8) LOG "AD Plant Proximity" (km)	-0.38 (-11.4, 11.99)	-0.09 (-3.03, 2.92)	0.09 (-2.81, 3.10)	0.30 (-8.45, 9.90)
(X8-INT A) Nearest AD Plant Output (kWe)	0.69 (-3.65, 5.23)	0.56 (-2.96, 4.22)	-0.52 (-3.80, 2.86)	-2.12 (-14.65, 12.23)
(X8-INT B) Influence of "Crop" Fed AD Plants (%)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	-0.33 (-13.02, 14.20)
(X8) : (X8-INT A)	0.90 (-10.06, 13.20)	0.18 (-2.11, 2.53)	0.12 (-1.44, 1.71)	1.81 (-19.10, 28.13)
(X8) : (X8-INT B)	-2.94 (-9.37, 3.93)	-0.75 (-2.47, 0.98)	0.75 (2.51, -0.97)	-10.75 (-31.20, 15.77)
(X8-INT A) : (X8-INT B)	0.36 (-1.31, 2.07)	0.29 (-1.06, 1.68)	-0.27 (-1.55, 1.00)	5.08 (-16.24, 31.84)
(X8) : (X8-INT A) : (X8-INT B)	-3.05 (-8.40, 2.60)	-0.62 (-1.75, 0.52)	-0.42 (-1.19, 0.35)	33.70 (-21.39, 127.41)

Table 7-8 B: Significant sub-regional multi-level model estimated changes (£/ha) in rental price on agricultural land valued at £156.68 per ha, associated with a percentile unit shift on an independent variable away from its median (50th percentile) value.

	Change in rental price (£/ha) associated with the difference between the Nth percentile and the median value of an independent variable (95% confidence interval)			
	1st Percentile	**25th Percentile**	**75th Percentile**	**99th Percentile**
(X1) Land Covered by FAT Agreements (%)	--	--	-2.90	-20.98
(X2) Agricultural Land Classification (ALC)	+61.59	+6.37	-14.69	-42.50
(X6) Maize Coverage (ha)	-1.55	-1.37	+3.68	+24.30

Green Cells = Significant at the 0.05 level, White Cells = Correlation significant at the 0.10 level

Under various multilevel modelling schemes, proximity to, or any of the AD plant interaction effects, were not observed to have a significant national level of influence on agricultural land rental prices. The influence of AD plants was then investigated through Geographically Weighted Regression (GWR) to determine whether this is a highly localised phenomenon.

7.2.3 Spatial regression: local model

Geographically weighted regression (GWR): model validation

Preliminary OLS modelling provided a relatively poor goodness-of-fit (R^2=0.07) on an acceptable list of independent variables (F-test <0.01). A significant, but weak, level of spatial autocorrelation was observed nationally amongst the OLS model residuals (P<0.01), with the use of 'global' spatial modelling approaches addressing concerns of observational independence when describing relationships at a national level. 'Local' spatial modelling in the form of Geographically Weighted Regression (GWR), will now create coefficients unique to each location (spatially varying) enabling the richness of the underlying data to be explored. Through embracing the concept of localised interactions rather than the removal of spatial structures, this method can investigate local responses which may have been smoothed away by modelling strategies which provide coefficients representative of national rates of change.

GWR models constructed with a sharp cut-off bandwidth scheme, placing weight on only a few observations of immediate proximity, may offer a near perfect fit (as measured by the R-Squared) but at a cost of increased model complexity. In practice, the simplest model is preferred if the latter offers little improvement (bias-variance trade-off). For instance, GWR models constructed from small sub-sets are likely to effectively fit the data, but their estimates are likely to be unreliable because the estimates exhibit large variances due to the limited degrees of freedom in the local model fitting. GWR models constructed from a majority of available observations will yield strongly biased estimates comparable to their OLS counterpart. A comprehensive measure of GWR model performance outlined by Jephcote *et al.,* (2014) was subsequently applied to weighting schemes ranging from the 100 to 40 Nearest Neighbour (NN) observations (Table 7-9).

Global Moran's I tests examining the spatial distribution of residuals indicated significant dispersion for all of the explored GWR weighting schemes (P<0.05). This indicates that a satisfactory calibration of the dataset's spatial components is achieved. The Kolmogorov-Smirnov Distribution Statistic rejected the possibility of a non-normal distribution within all GWR residuals (P>0.05), indicating acceptable levels of model behaviour and validity of model diagnostics. It should however be noted that some observations were omitted when creating increasingly localised models. This occurred on occasions where a lack of variability was found to exist in the AD plant interaction effects, preventing the creation of a local coefficient and therefore overall model convergence. This starts to become problematic when creating local regression models from less than 60NN.

To assist the process of model selection, a performance metric (GWR Model Index) was created to account for the number of available observations modelled, R^2 goodness-of-fit, and the AICc score describing the relative goodness-of-fit in relation to the corrected degree of freedom. GWR models with a weighting scheme of <70NN were found to exceed the OLS models performance metric value, indicating issues related to model complexity. Four F-test approaches to calculating the effective degrees of freedom from a GWR models RSS provided approximate likelihood ratio values, to compare GWR and OLS model abilities of reproducing the original dataset (Brunsdon *et al.,* 1999; Leung *et al.,* 2000; Fotheringham *et al.,* 2002). GWR F-tests indicated a relative improvement on performance from the OLS modelling strategy for all explored weighting schemes including >40NN ($P<0.05$). Based on the above information, a GWR model with a weighting scheme on the 70NN was deemed to provide the maximum level of prediction (R^2=0.54) within an acceptable level of performance.

GWR modelling techniques have previously paid only a limited amount of attention to standard diagnostic techniques, despite being susceptible to issues of multicollinearity (Wheeler and Tiefeldsdorf, 2005). To address these concerns, the GWR model constructed from a 70NN bi-square adaptive weighting scheme was tested by the 'usdm 1.1-12' [R] package's Variance Inflation Factor (VIF) diagnostic tool. No issues of multicollinearity were detected between GWR coefficients (excluding interaction effects), with VIF values ranging from 1.19 to 3.53 for the directly measured dependent variables ($\mathbf{X_{0\text{-}8}}$, $\mathbf{X_{INT\ A\text{-}B}}$), with the Intercept ($\mathbf{X_0}$) recording a VIF value of 3.67.

Table 7-9 Statistical measures of OLS and GWR performance for models exploring the relationship between agricultural land rental prices, land characteristics and proxies associated with the production-conversion process of energy crops in England and Wales

	Model Convergence: Observations (Total %)	Goodness-Of-Fit Measures		Relative Goodness-Of-Fit: Accuracy Vs. Complexity		GWR Model Index	Residual Patterning		F-Test: Relative Improvement GWR Vs. OLS (P-Value)			
		R^2	RSS	AIC	AICc		K-S Test (P-Value)	Moran's I (Z-Score)	BFC-F (1999)	FBC-F (2002)	LMZ-F1 (2000)	LMZ-F2 (2000)
OLS	682 (100%)	0.05	27.61	-219.62	-218.80	-0.36	0.18	9.74	--	--	--	--
GWR 100NN	629 (92%)	0.46	14.84	-407.45	-122.82	-1.07	0.66	-2.79	0.00	0.00	0.01	0.00
GWR 90NN	626 (92%)	0.49	14.10	-419.81	-94.42	-0.99	0.66	-2.88	0.00	0.00	0.01	0.00
GWR 80NN	617 (90%)	0.51	13.08	-433.23	-57.54	-0.82	0.40	-2.91	0.00	0.00	0.01	0.00
GWR 70NN	593 (87%)	0.54	11.77	-434.27	1.47	-0.40	0.29	-3.08	0.00	0.00	0.01	0.01
GWR 60NN	569 (83%)	0.60	9.75	-471.24	68.38	-0.05	0.21	-2.94	0.00	0.00	0.01	0.01
GWR 50NN	485 (71%)	0.65	7.57	-419.26	187.31	1.26	0.13	-2.85	0.00	0.00	0.01	0.04
GWR 40NN	409 (60%)	0.75	4.47	-462.35	320.87	2.43	0.32	-2.88	0.00	0.00	0.00	0.07

GWR Model Index: Collective indicator of model performance calculated via: ∑ "RSS (Z-Score) + AICc (Z-Score) + Missing Observations Count (Z-Score)"
K-S Test: Kolmogorov-Smirnov test for normal distribution with the residuals. Reject Null hypothesis of non-normal distribution where P-Value >0.05
Moran's I: Test for spatial patterning in the residuals, with neighbours classed by a 100 km fixed distance row-standardised weighting. 95% significance level Z-Score: ≤-1.98 (Dispersion) & ≥1.98 (Clustering)

Model outputs

Table 7-10 summarises the OLS (National) and GWR (Local) models examining the concurrent effects of agro-economic variables on land rental values, with the primary influence of AD plants measured in terms of proximity.

Local regression models with a 70NN 'Bi-Square Adaptive' weighting scheme collectively indicate a marked modelling improvement both in terms of predictability (Quasi-Global R^2 = 0.54), and by a 57.4% reduction on the OLS mean squared errors value. Although the global regression model may misrepresent local conditions and result in weaker relationships than the GWR model, such techniques are of a complementary nature; with global models defining significant attributes across a study area, whose interactions and likelihood may then be explored spatially by GWR.

Figure 7-3 Geographically Weighted Regression (GWR) local linear model performance (R-Square) under a 70 Nearest Neighbour (NN) Bisquare Adaptive weighting scheme

Figure 7-3 displays the spatial distribution of local R-square values generated by the individual regression models constructed at each observation grid, which collectively form the GWR model. Geographic variations in these values demonstrate how the combined statistical effect of explanatory variables on land rental value differs across England and Wales. The strongest model performances for an 80NN scheme are found between Lichfield to Preston (R^2>0.59), Reading and the South Downs national park (R^2 >0.67), and around the Bath-Bristol area (R^2 >0.61). The weakest model performances occurred throughout South Wales (R^2 0.27-0.39) and a band of land running north-east from the Lake District to Newcastle (R^2 0.27-0.40). Throughout England and Wales, residual plots alternate between over and under predicting, suggesting that the presence of extremely localised factors that influence rent perhaps remain uncaptured. The random spatial positioning of residuals (Moran's I P-Value <0.05) suggest these influences have been accounted for under the current weighting structure, but in an over-smoothed manner.

A fundamental assumption of the preceding OLS model is that a universal rate of change occurs across space, as denoted by fixed parameter coefficients; however the spatial model outputs summarised in Table 7-10 confirm the presence of spatial non-stationarity, whereby the direction and/or magnitude of a given influence differs throughout the study area.

Table 7-11 provides a regional summary of the geometric change (%) in rent from agro-economic influence where local coefficients met the desired statistical requirement ($P \leq 0.05$). Land where maize crops are currently grown appears to, on average, result in an increased rental price across multiple OSGB 10 km^2 cells in Wales (+28.0%), the South West (+14.7%), and the South East (+2.9%). It is only the East Midlands (-6.1%) and Yorkshire and Humber (-15.3%) where land set aside for maize cropping results in a slightly reduced rental price. Looking to the future, agricultural land deemed suitable for the growth of maize was found to command a higher price across multiple OSGB 10 km^2 cells in the South East (+13.0%), after adjusting for land productivity as described by the ALC. Land suited for maize crops in the North East (-51.2%) and Wales (-36.5%) was associated with a negative influence on land rental prices.

The influence of Anaerobic Digestion (AD) plants as indicated by proximity, was associated with raised rental prices in multiple OSGB 10 km^2 cells across Wales (+34.2%), the East of England (+14.8%), and the North West (+13.7%). In contrast, land in the East Midlands (-65.7%) and the South East (-14.5%) was associated with a decrease in rental prices, with increasing proximity to Anaerobic Digestion (AD) Plants. The GWR mapped outputs make it easier to better understand this relationship (Figure 7-4). The influence of AD plants as indicated by proximity interacting with energy output levels, was associated with raised rental prices in multiple OSGB 10 km^2 cells across the East Midlands (+26.3%), the South East (+26.2%), the North West (+25.9%) and the East of England (+21.7%). In contrast, a negative response on rental prices was modelled in multiple OSGB 10 km^2 cells across Yorkshire and Humber (-31.5%). Caution should be taken when interpreting the additional interaction effects which provide wildly fluctuating and high magnitude responses. These effects suggest issues of over-modelling and the capture of another process.

Table 7-10 70NN Geographically Weighted Regression (GWR) model of LOG10 transformed agricultural land rental prices (£/ha) in relation to agro-economic influences of interest

	OLS Linear Regression (N=682)			Linear 70 Nearest Neighbours Bisquare-Adaptive GWR (N=593)					
								% Grids P≤0.05 (BH P≤0.05)	
	β Value	Std. Error	P Value	Min. β	Med. β	Max. β	Std. Error	(+) β	(-) β
(X0) Intercept	2.20E+00	8.66E-03	0.000	-2.14E+00	2.14E+00	3.69E+00	1.40E-02	93.8 (93.8)	0 (0)
(X1) Land Covered by FAT Agreements (%)	-4.21E-04	2.51E-04	0.094	-4.48E-03	-4.85E-04	1.83E-03	4.71E-05	0 (0)	10.4 (0)
(X2) Agricultural Land Classification (ALC)	-5.13E-02	1.58E-02	0.001	-3.43E-01	-7.68E-02	1.68E-01	3.88E-03	0 (0)	14.1 (0)
(X3) LOG "Motorway Proximity" (km)	1.07E-02	2.26E-02	0.635	-6.16E-01	1.09E-03	5.52E-01	6.21E-03	4.1 (0)	1.6 (0)
(X4) LOG "Urban Proximity + 1" (km)	6.27E-02	3.16E-02	0.048	-5.02E-01	-7.00E-03	5.56E-01	7.72E-03	2.8 (0)	9.6 (0)
(X5) Carstair's Deprivation Index (z-score)	6.90E-03	3.67E-03	0.061	-6.76E-02	-1.71E-03	3.84E-02	6.61E-04	0.3 (0)	3.7 (0)
(X6) Maize Coverage (ha)	4.15E-05	4.23E-05	0.326	-2.39E-03	1.18E-05	2.46E-03	2.63E-05	13.1 (2.1)	4.1 (0)
(X7) Agricultural Land Suited for Maize (%)	1.36E-04	3.01E-04	0.652	-1.33E-02	2.19E-04	1.13E-02	1.22E-04	4.9 (0)	0.2 (0)
(X8) LOG "AD Plant Proximity" (km)	-2.44E-02	3.21E-02	0.448	-2.89E+01	1.52E-02	1.07E+01	8.04E-02	3.1 (0)	4.4 (0)
(X8-INT A) Nearest AD Plant Output (kWe)	-2.11E-06	1.85E-05	0.910	-8.15E-03	3.52E-05	8.77E-03	3.98E-05	7.1 (0)	2.9 (0)
(X8-INT B) Influence of "Crop" Fed AD Plants (%)	-5.88E-05	3.02E-04	0.846	-2.31E-01	-7.43E-04	8.35E-02	6.78E-04	1.3 (0)	9.7 (0)
(X8) : (X8-INT A)	9.87E-06	5.46E-05	0.857	-5.75E-02	-1.51E-04	6.12E-02	2.47E-04	1.9 (0)	3.7 (0)
(X8) : (X8-INT B)	-7.64E-04	1.12E-03	0.494	-1.62E+00	3.89E-03	6.24E-01	4.52E-03	2.8 (0)	1 (0)
(X8-INT A) : (X8-INT B)	1.58E-07	4.21E-07	0.708	-4.61E-04	6.14E-08	4.95E-04	2.15E-06	3.1 (0)	3.4 (0)
(X8) : (X8-INT A) : (X8-INT B)	1.15E-06	1.58E-06	0.469	-3.28E-03	4.95E-06	3.46E-03	1.38E-05	2.8 (0)	2.8 (0)
R-Square	0.05			0.54					
Residual Sum Of Squares (RSS)	27.61			11.77					
Mean Squared Error (MSE)	0.04			0.02					
AIC	-219.62			-434.27					
AICc	-218.80			1.47					
F-Test	< 0.01			< 0.01					

BH: Benjamini-Hochberg (B-H) False Discovery Rate conservatively adjusted p-value (Thissen *et al.,* 2002)

Table 7-11 GWR modelled regional 'Average (Count)' influence on land rental prices from an individual agro-economic variable (P ≤0.05), if all other independent variables were to have zero influence

	East Midlands	East of England	North East	North West	South East	South West	Wales	West Midlands	Yorkshire and Humber
Intercept (£/ha)	146.2 (80)	107.3 (57)	257.5 (33)	190.4 (69)	95.4 (62)	120.9 (87)	168.3 (78)	142.8 (56)	225.3 (57)
(X1) **Land Covered by FAT Agreements (%)** P	--	--	9.5 (9)	6.5 (3)	2.1 (6)	1.5 (45)	-29.7 (1)	--	--
(X2) **Agricultural Land Classification (ALC)** P	-9.0 (24)	66.4 (10)	--	3.0 (6)	12.9 (7)	18.2 (3)	--	-5.0 (14)	3.0 (23)
(X3) **LOG10 "Motorway Proximity" (km)** P	--	54.4 (12)	--	36.8 (3)	--	-9.3 (10)	-28.2 (10)	--	--
(X4) **LOG10 "Urban Proximity + 1" (km)** P	--	-3.7 (9)	--	--	25.1 (28)	7.3 (10)	28.3 (9)	11.9 (12)	3.0 (8)
(X5) **Carstair's Deprivation Index (z-score)** P	-19.7 (1)	16.3 (12)	--	--	6.5 (10)	--	--	--	-1.9 (2)
(X6) **Maize Coverage (ha)** P	-6.1 (20)	13.7 (12)	--	15.1 (1)	2.9 (6)	14.7 (48)	28.0 (11)	--	-15.3 (8)
(X7) **Agricultural Land Suited for Maize (%)**	--	--	-51.3 (19)	48.4 (1)	13.0 (3)	--	-36.5 (7)	--	22.5 (1)
(X8) **LOG10 "AD Plant Proximity" (km)** P	-65.7 (3)	14.8 (10)	--	13.7 (20)	-14.5 (6)	-45.7 (1)	34.2 (4)	-13.0 (1)	30.0 (1)
(X8-INT A) Nearest AD Plant Output (kWe)	26 (12)	37.7 (8)	--	-46.4 (8)	-25.4 (8)	-42.1 (7)	266.8 (13)	-20.4 (2)	-1.7 (4)
(X8-INT B) Influence of "Crop" Fed ADP	30.4 (8)	-95.9 (1)	--	10.2 (17)	4.8 (20)	19.3 (2)	25.6 (16)	9.5 (3)	19.5 (1)
(X8 * X8A) P	26.3 (9)	21.7 (5)	--	25.9 (2)	26.2 (5)	19.8 (1)	-37.2 (1)	-0.3 (1)	-11.8 (11)
(X8 * X8B) P	10.6 (5)	408.6 (8)	--	336.9 (3)	15.9 (5)	--	--	--	-19.9 (2)
(X8A * X8B) P	2.8 (8)	1915.7 (1)	--	29.7 (3)	11.6 (4)	--	-69.4 (11)	-10.5 (10)	54.4 (3)
(X8 * X8A * X8B) P	25.8 (3)	224.9 (11)	--	1165.9 (3)	17.1 (6)	--	56.7 (1)	-8.0 (2)	-17.7 (8)
Residuals P	6.5 (80)	7.7 (62)	3.4 (33)	5.5 (69)	3.9 (62)	2.5 (87)	6.6 (86)	4.0 (57)	7.8 (57)

P = Percent change in rent (£/ha) for a the recorded magnitude of a singularly held variable of interest

In Figure 7-4 the left-sided maps display the local GWR modelled baseline in land rent (£/ha), or GWR modelled geometric increases in rent (%) associated with an individually measured agro-economic influence. The right-hand-side adjacent map indicates where the trends for a given variable are of significance (P≤0.05), and identifies the areas where interpretation of the results should occur.

Maize Coverage

In the modelled outputs, AD proximity (and its various interaction effects) is considered to draw out the influence on rent from the demand for energy crops, which leaves the outputs associated with maize coverage (ha) to act as a proxy for the demand for maize as cattle fodder. To clarify, maize coverage (ha) without the inclusion of AD plant variables, acts as a combined measure of the impact from the fodder and energy components of maize.

The growth of maize is seen to have a significant influence on increasing land rental prices within three unique locations (P≤0.05):

- The first cluster consists of nine cells located close to the North Wales city of Bangor, which are associated with a 22.7 to 44.5% (95% CI: 0.9 to 100.5) geometric increase in rent (Figure 7-4). Currently low levels of maize are grown here (on average 8.67 ha per OSGB 10 km^2 grid cell), but the crop would appear to command a relatively high price.
- A second cluster comprising of eight cells extends from Bury St Edmunds to Ipswich (Suffolk), and is associated with a 6.9 to 38.4% (95% CI: 1.0 to 77.4) geometric increase in rent (Figure 7-4). On average, 38.4 ha of maize is grown per OSGB 10 km^2 grid cell, a value that lies well below the expected national cropping levels (143.5 ha). It should be noted that this cluster falls within a 5 to 40 km distance to a large mixed-feed AD plant (1400 kWe).
- A third cluster of 20 cells associated with a 3.7 to 89.1% (95% CI: 0.5 to 185.1) geometric increase in rent spreads from the Somerset town Taunton to the Devonshire city of Exeter (Figure 7 4). On average, 537.54 ha of maize is grown per OSGB 10 km^2 grid cell, but only 29.5% of the land is deemed suitable for the growth of maize crops. This cluster reflects an area where maize is traditionally grown as fodder for beef and dairy herds within the immediate vicinity. Two small mixed-feed AD plants are within the immediate vicinity (80 kWe and 3.5 kWe), but these are likely to have minimal influence on maize demand, with the manure from nearby herds considered a more viable fuel source. This cluster is surrounded by 19 cells where the growth of maize is seen to decrease rental values. Here, an average of 50.80 ha of maize is grown per OSGB 10 km^2 grid cell, and only 4.5% of the land is deemed suitable for the growth of maize crops.

The growth of maize is also seen to have a significant influence in decreasing land rental prices within a single key location (P≤0.05):

- The first cluster consists of 19 cells covering the county of Lincolnshire that are associated with a -26.7 to -4.05% (95% CI: -44.5 to -0.1) geometric increase in rent (Figure 7-4). Currently low levels of maize are grown here (on average 43.62 ha per OSGB 10 km^2 grid cell), yet 86.4% of the land is deemed suitable for the growth of maize crops. The centre of this cluster is within close proximity to a large (3000 kWe) and medium (300 kWe) food-waste fed AD plant. It would appear that crops grown specifically for the purpose of AD is currently of limited interest in Lincolnshire.

- A large crop-fed AD plant in Nottingham (2000 kWe), is located adjacent to the lower south-western edge of this cluster. The data significantly associate the 530.08 ha of maize grown with a 77.6% (95% CI: 10.1 to 186.3%) geometric increase in rent. Maize crops grown up to 30 km northwards also appear to result in raised land rental prices. It would appear that the measures of AD plants may not entirely remove the energy-crop component if a highly-localised influence exists.

Agricultural land deemed suitable for the growth of maize was found to significantly influence land rental prices within three locations (P≤0.05):

- The first cluster consists of 19 cells in the immediate vicinity to the Northumberland city of Newcastle, which are associated with a -59.0 to -29.2% (95% CI: -81.4 to -1.5) geometric reduction in rent (Figure 7-4). Less than 1% of the land in these OSGB 10 km^2 grid cells is considered suitable for the growth of maize, with on average only 7.35 ha of maize currently grown per cell. Demand from AD also appears limited, with only a single small mixed-feed plant (75 kWe) located in the immediate vicinity.

- The second cluster of seven cells falls within the previously explored high rental maize cropping area around the North Wales city of Bangor (Figure 7-4). Here, the unsuitability of land for growing maize is thought to provide a -44.5 to -19.1% (95% CI: -68.5 to -0.9) geometric decrease in rent.

- A third cluster comprised of two cells close to the East Sussex coastline, associate land suitability for the growth of maize with an 11.1 to 25.2% (95% CI: 0.5 to 55.5) geometric increase in rent (Figure 7-4). Currently 0 ha of maize are grown in both locations, which are considered to have 51.2% and 70.5% of their land suitable for the growth of maize respectively. The nearest AD plant is more than 30 km away.

AD Plant Proximity

Proximity to AD plants is seen to have a significant influence in raising land rental prices within three unique locations (P≤0.05):

- The first cluster is located in Cumbria, and consists of 13 cells extending from Carlisle to Keswick (FIGURE 4). The influence on rental price is of a particularly high magnitude in the cell inclusive of (198.2% [95% CI: 6.5 to 735.0]) and immediately adjacent (143.0% [95% CI: 2.1 to 478.5]) to a medium mixed-fed AD plant (500 kWe). In addition, a large crop-fed AD plant (1200 kWe) is situated 8 km to the west, with the nearest cell in this cluster attributing its presence with a 55.8% (95% CI: 10.9 to 118.9) increase in rent. The remaining cells on average associate a 27.4% increase in rent to AD plant proximity.

- A second cluster comprising of three cells to the north of Norwich (Norfolk), are associated with a 114.7 to 134.1% (95% CI: 3.24 to 430.7) geometric increase in rent (Figure 7-4). Two large crop-fed AD plants are positioned 3 km to the west (>1400 kWe), with a small manure-fed AD plant 15 km to the west (140 kWe).

- A single cell with a significantly high rental response (10.7% [95% CI: 0.8 to 67.6]) is located in the East Riding of Yorkshire. A medium mixed-fed AD plant (500 kWe) is located 13 km to the north.

At the other end of the spectrum, a cluster of five cells around Ipswich (Suffolk) were associated with an average geometric decrease in rental prices ranging from -33.6 to -22.5% (95% CI: -54.56 to -3.07), and are more than 40 km from the nearest AD plant (Mixed-fed 1400 kWe output). Likewise, a single cell within Carmarthenshire is located more than 45 km from the nearest AD plant (Manure-fed 3 kWe output), and is associated with a -58.0% (95% CI: -80.9 to -8.1) geometric decrease in rent.

Two oddities, comprising of three cells in Conwy and a single cell south of London, are situated more than 55 km away from the nearest AD plant, yet record this influence to increase their agricultural rental prices. It is likely that this part of the model's signal is being used to capture a separate influence of rental prices at these locations.

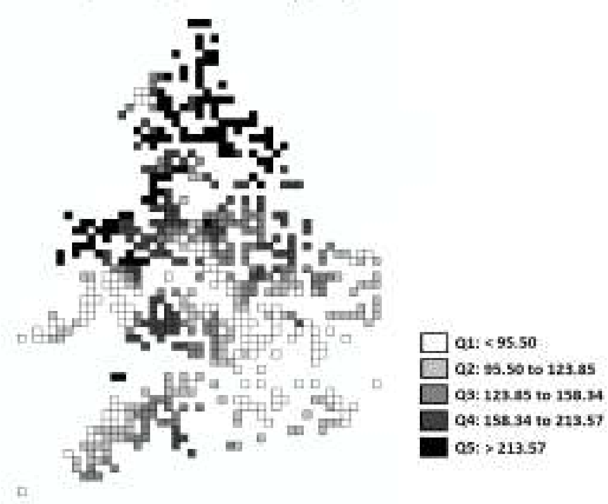
Interestingly, proximity to AD plants has a significant negative impact on land rental prices within three unique locations ($P \leq 0.05$), further highlighting the importance of localised modelling to capture non-stationary relationships:

- The first cluster consisting of 13 cells extends from the Oxfordshire market town of Banbury to Milton Keynes (Figure 7-4). The negative influence on rental price is of a particularly strong magnitude (-86.1% [95% CI: -31.2 to -14.8]) in the cell inclusive of a medium mixed-fed AD plant (499 kWe). The remaining cells are linked to a -47.9% geometric reduction in rental prices, the effect of which diminishes with distance from the AD plant in question.

- A second cluster comprising of four cells is positioned between the Staffordshire towns of Crewe and Leek (Figure 7-4). The negative influence on rental price is of a particularly strong magnitude (-90.9% [95% CI: -98.2 to -24.2]) in the cell inclusive of a small mixed-fed AD plant (100 kWe). A second small food-waste fed AD plant is located 6 km to the north-west (75 kWe). The remaining cells are linked to a -36.1% geometric reduction in rental prices, the effect of which diminishes with distance from the AD plant in question.

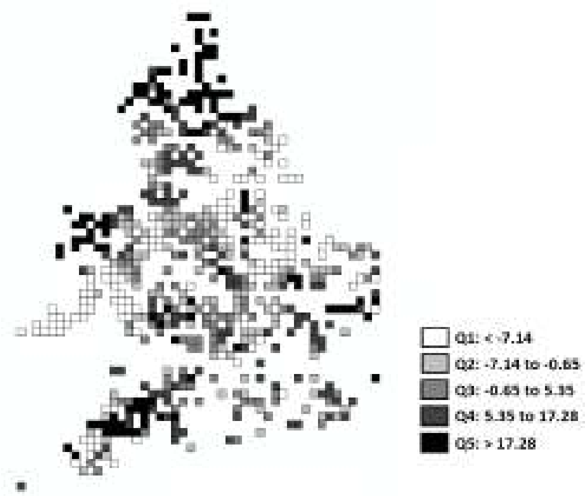
- A single cell associated with a significant geometric reduction in rent (-45.7% [95% CI: -67.1 to -10.3]) is located in the South West county of Wiltshire (Figure 7-4). A medium mixed-fed AD plant (499 kWe) is located 6 km to the east.

Baseline (Intercept) Land Value (£/ha)



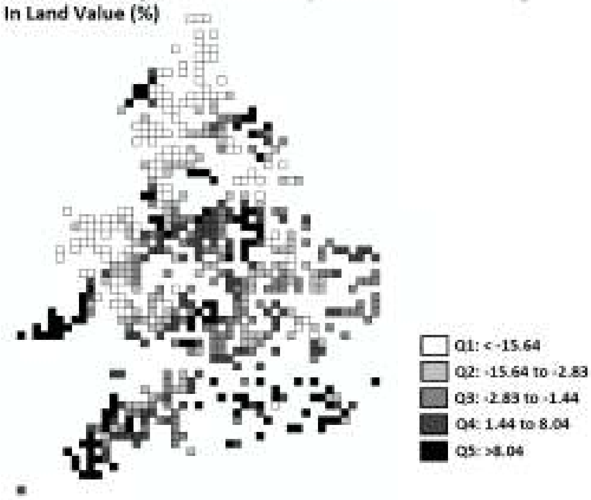
Baseline (Intercept) Significance

Maize Coverage: Expected Geometric Change In Land Value (%)

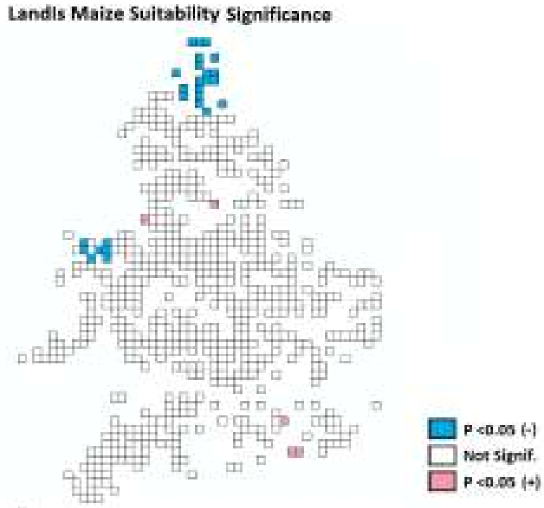


JAC/WG-IACS Maize Coverage Significance

Maize Suited Agricultural Land: Expected Geometric Change In Land Value (%)



LandIs Maize Suitability Significance



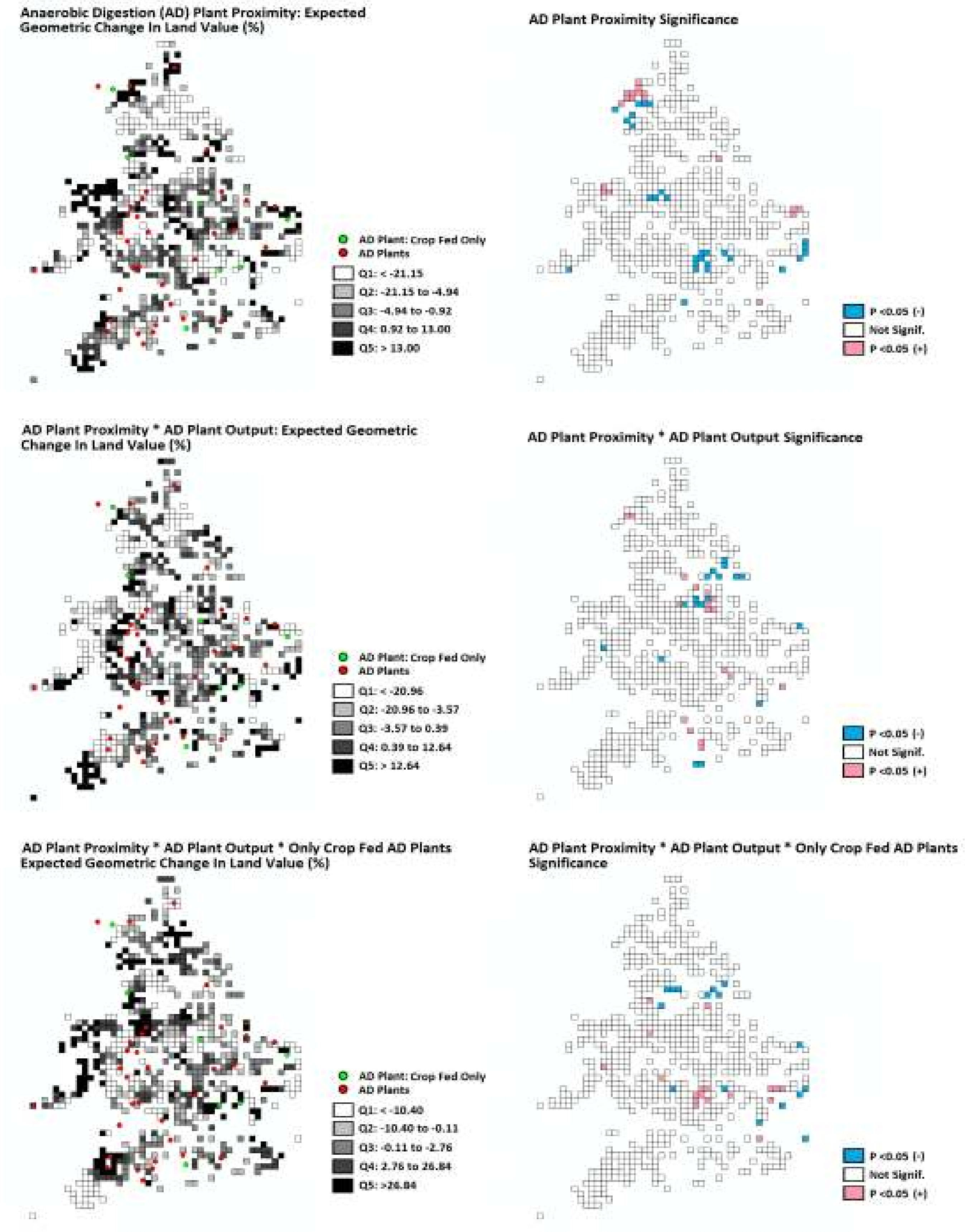


Figure 7-4 Geographically Weighted Regression (GWR) modelled quantile plots of the rental baseline in agricultural land (£/ha), and geometric increases in rent (%) instigated by individually measured agro-economic influence if all other independent variables were to have zero influence.

AD Plant Proximity, Output, and Feed Type

The interaction between the nearest AD plant and a given OSGB 10 km^2 grid cell, in terms of output, feed type, and proximity, are shown to be of a significant influence in increasing land rental prices within three unique locations ($P \leq 0.05$):

- The first cluster comprised of seven cells, extends from the Oxfordshire market town of Banbury to Milton Keynes, and is associated with a 5.7 to 44.7% (95% CI: 0.1 to 101.0) geometric increase in rent (Figure 7-4). Rental prices are of a particularly raised magnitude in the cell (44.7% [95% CI: 4.1 to 101.1]) inclusive of the medium mixed-fed AD plant (499 kWe).

- For this cluster, proximity to an AD plant was previously shown to result in a reduction of the agricultural land rental prices. However, when taking into account the demand (crop-fed only sites) and activity (AD output) we can see that rise in rental prices is associated with this AD plant.

- A second cluster inclusive of three cells near to the Suffolk market town of Bury St Edmunds, is associated with a 52.6 to 260.1% (95% CI: -0.05 to 1078.1) geometric increase in rent (Figure 7-4). On average only 9.7 ha of maize is grown per OSGB 10 km^2 grid cell, and only 10.0% of the land is deemed suitable for the growth of maize. It would appear that even though AD plants are impacting rental values at these locations, such grids are unable to effectively respond to such a demand.

- A third cluster consisting of four cells situated close to the Yorkshire town of Goole, is associated with a geometric decrease of -11.7 to -2.3% (95% CI: -20.0 to 0.0) in the rental response (Figure 7-4).

- For one cell, proximity to the medium size mixed AD plant (500 kWe) was previously shown to increase rental prices by 10.7%. However, when taking into account the demand (crop-fed only sites) and activity (AD output) we can see that a decrease in rental prices of -3.6% (95% CI: -5.8 to -1.4%) is associated with this AD plant. It would appear that this site sources its feed locally, but as it is not restricted to a certain feed type and has only a moderate output there is not a strong demand for energy crops.

Benjamini-Hochberg (B-H) False Discovery Rate

With spatially correlated data, a reduction in the group variance of parameter estimates may occur where local response coincides with well-defined events (increased likelihood of Type 1 'false-positive' errors), or in areas where the recorded variable is close to zero and therefore unable to influence the outcome (increased likelihood of Type 2 'false-negative' errors). Through placing prominence on local specific outcomes, GWR is able to account and adapt to differing low levels of within group variation across the dataset (localised clustering), minimising errors associated with the underlying data. However, constructing local regression models with a unique set of parameters and standard errors at each regression point, on which multiple t-tests of significance are conducted, will increase the likelihood of Type 1 errors.

Following Tsai (2011) and Ricardo da Silva and Fotheringham's (2015) exploration of multiple testing issues in GWR, the local p-values were corrected using Thissen *et al.,*'s (2002) implementation of the very conservative Benjamini-Hochberg (BH) false discovery rate procedure. The BH approach controls the false rate of discovery by sequentially comparing the observed p-value for each family of multiple test statistics, in order from largest to smallest, to compute a series of critical values determining local significance.

Table 7-10 shows that through using this adjustment measure, the only variable to produce local regression outputs of significance is the area of maize coverage (ha). The outputs of which are restricted to the previously described cluster extending from the Somerset town of Taunton to the Devonshire city of Exeter. However, the extremely conservative nature of this test should not automatically result in the discounting of the previously discussed relations of significance under standard test procedures. Interpretation is based on data analysis that needs to be confirmed by local case studies. This would further explore the reasons for the associations shown by the modelled data outputs.

7.3 Conclusions

A significant, yet weak, level of spatial autocorrelation was observed to exist in the LOG_{10} transformed dataset of FBS agricultural land rental prices (£/ha) at a national level ($P \leq 0.01$). It is likely that the true extent of autocorrelation would be substantially stronger if rental agreements were to exist as a continuous, rather than fragmented, surface.

Following the detection of spatial correlation in the residuals of the conventional multivariate regression, a spatial error model (SEM) constructed from an 80 km row-standardised continuity scheme (approximately 72 Nearest Neighbour (NN) weighting structure), was used to provide optimised fixed parameter estimates representative of the average response at a national level. Statistically significant underlying trends in the data at the 5% significance level identify:

- Upon removing the influence of agro-economic factors, the average baseline (intercept) price of rent across England and Wales equates to £163.49 (95% CI: 138.47 to 193.05) per ha.
- An inverse relationship between land rental price and the classification of land quality, where Grade 1 is deemed to be of 'excellent quality' and Grade 5 is 'very poor land restricted to permanent pasture'. This shows that as rental rates increase so does the quality of the agricultural land.
- An inverse relationship between land rental prices and the uptake of FAT tenancies. This perhaps reflects the stable income that a long-term agreement can provide.

Under various methods of 'global' spatial modelling, proximity to, or any of the AD plant interaction effects, were not observed to significantly influence agricultural land rental prices; as defined by the average national rate of change. Subsequently 'local' spatial modelling in the form of Geographically Weighted Regression (GWR) with a '70NN Bisquare-Adaptive' weighting scheme, was employed to construct location specific (spatially varying) coefficients. This allowed for the investigation of localised responses signals, which was potentially smoothed away by the preceding "global" modelling strategies.

The influence of Anaerobic Digestion (AD) plants as indicated by proximity, was associated with raised rental prices in multiple OSGB 10 km^2 cells across Wales (+34.2%), the East of England (+14.8%), and the North West (+13.7%). In contrast, land in the East Midlands (-65.7%) and South East (-14.5%) was associated with a decrease in rental prices with the influence of Anaerobic Digestion (AD) plants as indicated by proximity.

The interaction between the nearest AD plant and a given OSGB 10 km^2 grid cell, in terms of output, feed type, and proximity, are shown to be of significant influence in raising land rental prices within three unique locations at the 5% significance level:

- A cluster of seven cells located around the Oxfordshire market town of Banbury is associated with a 5.7 to 44.7% (95% CI: 0.1 to 101.0) geometric increase in rent from a medium mixed-fed AD Plant (499 kWe).
- A cluster of three cells near to the Suffolk market town of Bury St Edmunds is associated with a 52.6 to 260.1% (95% CI: -0.05 to 1078.1) geometric increase in rent. It would appear that even though AD plants are impacting rental values at these locations, such grids are unable to effectively respond to this demand, with the agricultural land in these cells deemed unsuitable for growing maize.
- A cluster of four cells situated close to the Yorkshire town of Goole is associated with a geometric decrease of -11.7 to -2.3% (95% CI: -20.0 to 0.0) in rental prices. It would appear that this site sources its feed locally, but as it is not restricted to a certain feed type and has only a moderate output (500 kWe) there is not a strong demand for energy crops.

When correcting GWR modelled outputs using the extremely conservative Benjamini-Hochberg (B-H) False Discovery Rate test, no relations were observed to be of significance between land rental prices and the influence of AD plants. Caution must therefore be taken when interpreting these outputs; with such trends requiring confirmation from local case studies.

7.4 References

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8 Appendix 2. Results for Individual WFD Management WMCs

8.1 Farmscoper Results

Table 8-1 Farmscoper results for individual WMCs that were originally growing maize for AD. Values expressed on a 'per hectare of land displaced' basis.

WMC	N (kg ha^{-1})	P (kg ha^{-1})	Sediment (kg ha^{-1})	Ammonia (kg ha^{-1})	Nitrous Oxide (kg ha^{-1})	Soil Carbon (t ha^{-1})	Energy Use (GJ ha^{-1})
Avon Warwickshire	5.22	0.22	149.56	-3.30	-0.06	-4.70	1072.48
Broadland Rivers	2.30	0.10	66.78	-4.14	-0.52	-3.70	982.92
Cam and Ely Ouse	-1.07	0.05	29.03	-5.00	-0.88	-3.24	876.20
Cherwell	10.51	0.20	158.64	-1.92	0.40	-5.80	1137.11
Colne	2.35	0.16	115.40	-4.27	-0.36	-2.99	1052.07
Combined Essex	-0.52	0.09	48.99	-5.26	-0.77	-2.97	953.72
Cotswolds and the Vale	9.59	0.12	95.31	-2.68	0.23	-4.76	1096.52
Derwent Humber	3.63	0.15	120.23	-3.50	-0.17	-3.44	971.08
Don and Rother	0.44	0.21	164.29	-5.03	-0.62	-3.64	975.73
Dorset	12.77	0.35	301.23	-1.50	0.60	-5.86	1149.58
East Devon	17.06	0.65	563.68	0.16	1.12	-7.10	1194.73
East Suffolk	-0.51	0.11	68.83	-5.15	-0.78	-3.60	918.39
Idle and Torne	1.21	0.05	31.93	-4.80	-0.62	-3.45	954.65
Isle of Wight	4.12	0.14	116.66	-3.71	-0.19	-3.06	1029.48
Louth Grimsby and Ancholme	0.08	0.10	67.86	-5.49	-0.75	-3.40	967.74
Lower Trent and Erewash	-1.12	0.11	72.11	-5.71	-0.86	-3.51	944.09
Medway	7.18	0.34	264.44	-2.04	0.30	-5.10	1086.53
Nene	-0.22	0.12	77.21	-5.36	-0.73	-4.13	977.80
New Forest	14.61	0.53	454.06	0.70	1.18	-7.93	1153.63
North Devon	18.57	0.49	452.54	0.25	1.24	-6.73	1205.56
North Kent	1.65	0.16	118.96	-4.86	-0.51	-4.20	1036.94

WMC	N (kg ha^{-1})	P (kg ha^{-1})	Sediment (kg ha^{-1})	Ammonia (kg ha^{-1})	Nitrous Oxide (kg ha^{-1})	Soil Carbon (t ha^{-1})	Energy Use (GJ ha^{-1})
North Norfolk	1.65	0.02	15.08	-3.80	-0.44	-2.80	926.31
North West Norfolk	1.08	0.05	32.21	-3.84	-0.50	-2.93	910.97
Old Bedford and Middle Level	-1.46	0.09	55.23	-4.94	-0.86	-3.57	855.01
Severn Middle Shropshire	3.57	0.15	128.52	-3.15	-0.09	-4.16	931.59
Severn Middle Worcestershire	4.54	0.17	131.29	-3.01	0.00	-4.24	987.41
Severn Uplands	5.82	0.49	424.37	-3.20	-0.02	-4.96	1029.03
Severn Vale	12.18	0.33	246.64	-0.94	0.67	-6.55	1157.32
South and West Somerset	15.84	0.46	383.95	-0.03	1.00	-7.29	1189.33
Stour	2.06	0.14	104.05	-4.12	-0.34	-3.58	1013.45
Swale, Ure, Nidd and Upper Ouse	2.29	0.42	336.93	-3.54	-0.22	-3.92	1014.53
Tamar	14.09	0.58	526.19	-0.67	0.91	-6.08	1120.69
Tame Anker and Mease	0.28	0.19	145.23	-5.02	-0.60	-4.02	929.50
Test and Itchen	4.93	0.06	49.65	-3.92	-0.14	-2.82	1030.53
Upper and Bedford Ouse	0.56	0.13	79.28	-5.28	-0.61	-3.90	1018.25
Upper Lee	0.88	0.14	79.69	-4.82	-0.52	-3.43	1045.28
Weaver and Gowy	12.87	0.44	382.31	-0.13	0.88	-6.95	1143.53
Welland	-1.08	0.12	79.85	-5.37	-0.79	-3.80	936.07
West Cornwall and the Fal	17.42	0.22	215.16	-0.04	1.07	-6.37	1124.44
Wharfe and Lower Ouse	-2.20	0.39	315.68	-5.00	-0.70	-3.14	921.63
Witham	-0.82	0.12	76.75	-5.21	-0.77	-3.37	961.03
Wye	9.17	0.46	401.38	-1.92	0.36	-5.65	1050.43

Values expressed on a 'per hectare of land displaced' basis.

Table 8-2 Farmscoper results for individual WMCs that were not originally growing maize for AD.

WMC	N (kg ha^{-1})	P (kg ha^{-1})	Sediment (kg ha^{-1})	Ammonia (kg ha^{-1})	Nitrous Oxide (kg ha^{-1})	Soil Carbon (t ha^{-1})	Energy Use (GJ ha^{-1})
Adur and Ouse	11.74911	0.457353	370.0571	-0.56051	0.771217	-6.173246	1170.503
Aire and Calder	17.4011	0.72254	636.6551	1.282347	1.444423	-8.404574	1249.37
Alt and Crossens	0.320396	0.200522	163.1783	-3.55795	-0.34402	-2.386275	859.5908
Arun and Western Streams	11.64275	0.284332	251.2964	-1.21965	0.596087	-5.776913	1097.567
Avon Bristol and North Somerset Streams	14.6959	0.393715	330.2964	-0.53396	0.858727	-6.741077	1181.703
Avon Hampshire	12.34448	0.103527	92.67787	-2.36133	0.366242	-4.927324	1107.462
Cuckmere and Pevensey Levels	14.05055	0.585799	473.6747	0.586093	1.150267	-7.511086	1220.6
Darent	10.24659	0.091421	73.06729	-3.11415	0.120361	-5.303793	1092.031
Dee	13.78004	0.451091	389.0915	-0.47932	0.838033	-7.548452	1198.964
Derwent Derbyshire	20.67572	0.51344	453.9805	1.448967	1.597534	-8.2728	1262.932
Derwent North West	6.029159	0.317551	286.8008	-0.12292	0.435983	-3.243459	617.3649
Douglas	14.20986	0.878134	768.6189	0.443654	1.10794	-7.261572	1198.95
Dove	19.65736	0.571951	501.1784	1.601518	1.577782	-8.658956	1269.735
East Hampshire	10.81821	0.20295	175.0225	-1.92598	0.46624	-4.959946	1121.716
Eden and Esk	15.40796	0.806274	722.2637	0.597243	1.187763	-7.111254	1219.405
Esk and Coast	13.9067	0.62002	540.9222	0.276505	1.053776	-7.256089	1212.691
Hull and East Riding	1.597466	0.095198	68.79323	-6.25905	-0.93877	-2.8156	939.0785
Irwell	22.54327	1.172495	1032.466	3.156041	2.103815	-9.801532	1330.442
Kennet	7.022454	0.144389	111.4317	-3.21105	0.022259	-4.16964	1059.543
Kent and Leven	25.79729	1.23739	1127.976	2.644519	2.099466	-9.294811	1302.417
Loddon	11.79534	0.238066	193.3104	-1.16126	0.592409	-6.633673	1123.187
London	10.96133	0.201912	147.0636	-0.60163	0.785463	-5.653419	1160.688
Lower Thames	7.222207	0.151648	110.7763	-3.0765	0.058461	-5.068667	1092.88
Lune	20.68921	1.583132	1391.4	2.508853	1.853838	-9.210375	1292.747
Mersey Estuary	9.075865	0.452598	390.9506	-1.31328	0.503169	-5.091487	1120.515
Mole	11.55186	0.35202	292.4028	-1.00372	0.669022	-6.22497	1146.91
North Cornwall, Seaton, Looe and Fowey	18.44295	0.476387	442.5987	0.092288	1.166638	-6.585994	1187.977

Table 8-2 Continued

WMC	N (kg ha^{-1})	P (kg ha^{-1})	Sediment (kg ha^{-1})	Ammonia (kg ha^{-1})	Nitrous Oxide (kg ha^{-1})	Soil Carbon (t ha^{-1})	Energy Use (GJ ha^{-1})
Northumberland Rivers	11.08929	0.421658	355.5233	-0.90824	0.662892	-6.236131	1169.604
Ribble	19.74148	1.529784	1339.336	2.738028	1.87214	-9.50862	1314.003
Roding, Beam and Ingrebourne	-0.22731	0.161702	100.7769	-5.14333	-0.68871	-3.1456	982.4998
Rother	8.733594	0.433506	339.6485	-1.02492	0.574263	-5.74067	1144.091
Soar	9.154424	0.254898	182.6869	-2.1612	0.258884	-5.750352	1127.974
South Devon	18.80153	0.681873	628.8623	0.167479	1.192389	-6.786547	1199.238
South Essex	9.26711	0.164292	114.5303	-0.92317	0.643861	-6.129173	1184.053
South West Lakes	20.03623	1.503087	1343.587	1.798884	1.659418	-8.28444	1263.076
Tees	6.055089	0.582273	487.0551	-2.9094	0.039846	-5.295125	1098.556
Teme	12.61487	0.287609	229.0654	-1.14185	0.664855	-5.938081	1144.302
Till	11.8893	0.261021	223.3058	-1.22037	0.63917	-5.81121	1148.063
Trent Valley Staffordshire	12.56353	0.363897	300.054	-1.10363	0.629125	-6.529241	1153.55
Tweed	6.216162	0.203843	131.8146	-2.15672	0.263567	-4.248737	1108.019
Tyne	16.02546	0.912872	794.2722	1.532678	1.465645	-8.27555	1266.321
Upper Mersey	18.59237	0.869858	762.2438	1.918085	1.62559	-8.656084	1253.392
Waver or Wampool	11.465	0.603853	545.3781	-0.23375	0.829062	-6.167736	1173.976
Wear	10.73694	0.60499	514.6403	-0.87836	0.702655	-6.635309	1182.609
Wey	13.1176	0.209669	172.8165	-1.1627	0.711428	-6.330255	1149.81
Wyre	15.71574	1.263593	1114.21	1.280505	1.336247	-8.187146	1246.088

8.2 EAgRET Results

Values expressed on a 'per hectare of land displaced' basis.

Table 8-3 EAgRET results for individual WMCs that were originally growing maize for AD.

WMC	CO_2 (kg ha^{-1})	Nitrous Oxide (kg ha^{-1})	GWP (kg ha^{-1} CO_2e)	Energy (GJ ha^{-1})	SO_4e (kg ha^{-1})	PO_4e (kg ha^{-1})
Avon Warwickshire	14.61	-1.07	-304.97	2.17	-48.01	-9.32
Broadland Rivers	-177.25	-1.64	-664.51	-0.22	-50.13	-9.68
Cam and Ely Ouse	-365.25	-2.00	-962.47	-2.06	-57.56	-11.07
Cherwell	184.33	-0.73	-32.53	4.07	-36.69	-7.28
Colne	-91.60	-1.29	-475.91	0.60	-53.76	-10.27
Combined Essex	-289.03	-1.69	-794.10	-1.15	-61.23	-11.69
Cotswolds and the Vale	81.86	-0.91	-187.95	2.76	-42.97	-8.38
Derwent Humber	-63.34	-1.09	-388.01	1.04	-46.57	-9.01
Don and Rother	-222.48	-1.56	-685.97	-0.34	-59.66	-11.43
Dorset	225.91	-0.63	37.25	4.46	-34.81	-6.93
East Devon	428.64	-0.21	364.59	6.62	-20.71	-4.38
East Suffolk	-311.17	-1.79	-843.74	-1.23	-60.26	-11.57
Idle and Torne	-238.35	-1.65	-729.08	-0.68	-57.35	-11.00
Isle of Wight	-58.14	-1.20	-414.91	0.87	-50.87	-9.75
Louth Grimsby and Ancholme	-270.69	-1.71	-780.54	-0.97	-62.90	-11.99
Lower Trent and Erewash	-327.93	-1.83	-874.39	-1.39	-66.22	-12.63
Medway	175.76	-0.69	-30.56	3.60	-33.77	-6.67
Nene	-263.56	-1.74	-783.05	-0.63	-63.83	-12.21
New Forest	498.54	0.00	499.54	7.41	-12.64	-2.91
North Devon	467.44	-0.14	427.10	6.69	-17.25	-3.70
North Kent	-156.11	-1.43	-582.57	0.48	-58.68	-11.23
North Norfolk	-168.19	-1.53	-624.59	-0.56	-46.27	-8.92
North West Norfolk	-185.51	-1.58	-657.28	-0.70	-45.21	-8.72
Old Bedford and Middle Level	-377.81	-1.92	-949.99	-1.85	-58.97	-11.37
Severn Middle Shropshire	-82.36	-1.07	-401.25	1.24	-46.66	-9.12
Severn Middle Worcestershire	-2.44	-0.96	-289.45	1.82	-43.07	-8.41
Severn Uplands	-10.54	-1.04	-320.23	2.10	-46.47	-9.09
Severn Vale	284.76	-0.50	135.55	5.27	-30.62	-6.20
South and West Somerset	389.91	-0.27	309.19	6.45	-23.13	-4.86
Stour	-113.13	-1.26	-488.53	0.67	-52.13	-10.01

Table 8-3: Continued						
WMC	**CO_2 (kg ha^{-1})**	**Nitrous Oxide (kg ha^{-1})**	**GWP (kg ha^{-1} CO_2e)**	**Energy (GJ ha^{-1})**	**SO_4e (kg ha^{-1})**	**PO_4e (kg ha^{-1})**
Swale, Ure, Nidd and Upper Ouse	-38.96	-1.12	-372.34	1.33	-45.91	-8.90
Tamar	340.40	-0.36	232.90	5.31	-24.27	-4.98
Tame Anker and Mease	-248.37	-1.53	-703.53	-0.33	-61.71	-11.86
Test and Itchen	-43.91	-1.15	-387.49	0.78	-49.82	-9.52
Upper and Bedford Ouse	-192.38	-1.53	-648.85	-0.05	-62.54	-11.93
Upper Lee	-154.67	-1.45	-586.13	0.19	-59.37	-11.33
Weaver and Gowy	345.01	-0.31	252.84	5.98	-24.46	-5.11
Welland	-296.98	-1.79	-829.48	-1.06	-62.94	-12.04
West Cornwall and the Fal	339.59	-0.28	256.45	5.69	-22.67	-4.74
Wharfe and Lower Ouse	-248.94	-1.54	-706.95	-0.79	-58.20	-11.16
Witham	-273.33	-1.75	-795.23	-1.05	-60.63	-11.58
Wye	117.26	-0.78	-114.86	3.48	-38.17	-7.60

Values expressed on a 'per hectare of land displaced' basis.

Table 8-4 EAgRET results for individual WMCs that were originally growing maize for AD

WMC	N Balance (kg ha^{-1})	P Balance (kg ha^{-1})	Abiotic Resource Use (kg ha^{-1} Sbe)	N Fert (kg ha^{-1})	P Fert (kg ha^{-1})
Avon Warwickshire	-107.92	-20.75	0.78	-55.89	11.22
Broadland Rivers	-91.76	-17.36	0.08	-56.92	8.05
Cam and Ely Ouse	-89.13	-17.32	-0.48	-64.21	4.79
Cherwell	-117.52	-25.37	1.53	-44.73	13.71
Colne	-93.63	-14.54	0.10	-60.92	9.83
Combined Essex	-91.30	-13.90	-0.40	-68.48	7.33
Cotswolds and the Vale	-108.03	-21.85	0.96	-50.59	12.12
Derwent Humber	-93.74	-19.91	0.39	-53.51	7.83
Don and Rother	-96.13	-17.09	-0.17	-67.21	7.31
Dorset	-120.33	-27.49	1.60	-42.75	13.75
East Devon	-131.68	-33.73	2.49	-28.66	15.75
East Suffolk	-94.72	-17.69	-0.33	-67.58	5.84
Idle and Torne	-92.00	-16.96	-0.23	-64.46	6.83
Isle of Wight	-93.68	-14.98	0.28	-57.91	10.18
Louth Grimsby and Ancholme	-91.95	-14.51	-0.45	-70.26	7.30
Lower Trent and Erewash	-94.71	-15.26	-0.55	-73.82	6.50
Medway	-109.98	-23.22	1.37	-41.01	12.83
Nene	-102.03	-16.94	-0.26	-71.68	7.82
New Forest	-135.55	-36.91	2.85	-20.35	15.78
North Devon	-126.14	-32.45	2.52	-24.74	15.96
North Kent	-105.31	-16.24	0.08	-66.56	10.26
North Norfolk	-83.97	-18.30	-0.08	-52.16	6.04
North West Norfolk	-84.41	-17.55	-0.07	-51.01	6.36
Old Bedford and Middle Level	-96.96	-19.88	-0.34	-66.10	4.48
Severn Middle Shropshire	-105.46	-26.47	0.57	-54.04	6.22
Severn Middle Worcestershire	-103.16	-24.18	0.72	-50.25	8.23
Severn Uplands	-110.02	-24.69	0.83	-54.39	9.32
Severn Vale	-127.12	-30.33	1.97	-38.82	14.51
South and West Somerset	-134.60	-34.02	2.46	-31.40	15.76
Stour	-102.13	-17.64	0.24	-59.44	9.52

Table 8-4 Continued.					
WMC	N Balance (kg ha^{-1})	P Balance (kg ha^{-1})	Abiotic Resource Use (kg ha^{-1} Sbe)	N Fert (kg ha^{-1})	P Fert (kg ha^{-1})
Swale, Ure, Nidd and Upper Ouse	-98.73	-20.88	0.48	-52.99	8.76
Tamar	-119.74	-31.29	2.00	-31.57	12.90
Tame Anker and Mease	-100.83	-19.70	-0.10	-69.65	6.17
Test and Itchen	-87.22	-15.04	0.09	-56.43	9.37
Upper and Bedford Ouse	-98.80	-15.38	-0.21	-70.32	8.94
Upper Lee	-98.69	-14.60	-0.06	-66.96	9.79
Weaver and Gowy	-133.38	-35.44	2.30	-32.58	13.90
Welland	-98.39	-17.17	-0.38	-70.46	6.53
West Cornwall and the Fal	-127.72	-34.70	2.17	-30.27	13.23
Wharfe and Lower Ouse	-90.98	-18.52	-0.31	-65.28	5.18
Witham	-93.60	-15.61	-0.40	-67.80	7.15
Wye	-119.02	-29.20	1.41	-46.14	10.59

Values expressed on a 'per hectare of land displaced' basis.

Table 8-5 EAgRET results for individual WMCs that were not originally growing maize for AD

WMC	CO_2 (kg ha^{-1})	Nitrous Oxide (kg ha^{-1})	GWP (kg ha^{-1} CO_2e)	Energy (GJ ha^{-1})	SO_4e (kg ha^{-1})	PO_4e (kg ha^{-1})
Adur and Ouse	350.24	-0.35	244.67	5.53	-24.47	-5.02
Aire and Calder	628.15	0.18	681.49	8.59	-5.84	-1.65
Alt and Crossens	-183.55	-1.16	-529.69	-0.22	-49.04	-9.49
Arun and Western Streams	210.86	-0.62	27.21	4.31	-33.40	-6.70
Avon Bristol and North Somerset Streams	334.81	-0.40	216.13	5.75	-27.31	-5.60
Avon Hampshire	112.62	-0.84	-137.24	3.12	-39.80	-7.81
Cuckmere and Pevensey Levels	528.71	-0.02	524.19	7.44	-12.91	-2.92
Darent	30.43	-1.02	-274.45	2.67	-47.90	-9.35
Dee	350.97	-0.41	228.45	6.22	-28.51	-5.86
Derwent Derbyshire	640.30	0.22	706.12	8.69	-5.27	-1.54
Derwent North West	196.46	-0.14	153.96	3.05	-11.84	-2.45
Douglas	489.33	-0.07	467.20	7.09	-15.25	-3.37
Dove	660.42	0.24	730.86	9.04	-5.24	-1.56
East Hampshire	184.42	-0.68	-16.94	3.65	-34.66	-6.84
Eden and Esk	509.48	-0.02	502.21	7.23	-13.84	-3.09
Esk and Coast	487.00	-0.10	457.48	7.08	-15.80	-3.46
Hull and East Riding	-413.25	-1.86	-968.63	-1.89	-74.95	-14.31
Irwell	908.50	0.75	1131.18	11.33	13.45	1.89
Kennet	22.46	-1.02	-282.91	1.98	-45.27	-8.76
Kent and Leven	825.97	0.59	1003.13	10.50	8.24	0.94
Loddon	211.23	-0.61	30.19	4.81	-35.12	-7.07
London	373.41	-0.34	272.55	5.40	-22.32	-4.56
Lower Thames	51.27	-1.02	-253.86	2.64	-46.40	-9.02
Lune	788.70	0.52	943.10	10.22	4.99	0.33
Mersey Estuary	244.69	-0.54	84.59	4.29	-30.36	-6.08
Mole	305.34	-0.47	164.37	5.18	-28.73	-5.81

Table 8-5 Continued.						
WMC	**CO_2 (kg ha^{-1})**	**Nitrous Oxide (kg ha^{-1})**	**GWP (kg ha^{-1} CO_2e)**	**Energy (GJ ha^{-1})**	**SO_4e (kg ha^{-1})**	**PO_4e (kg ha^{-1})**
North Cornwall, Seaton, Looe and Fowey	414.03	-0.23	346.97	6.30	-20.95	-4.40
Northumberland Rivers	322.51	-0.46	186.57	5.37	-28.12	-5.71
Ribble	831.87	0.60	1010.20	10.66	7.86	0.85
Roding, Beam and Ingrebourne	-254.59	-1.53	-711.90	-0.64	-60.89	-11.63
Rother	284.35	-0.45	149.64	4.80	-25.65	-5.20
Soar	134.69	-0.84	-114.47	3.74	-41.50	-8.20
South Devon	431.59	-0.19	374.81	6.51	-19.69	-4.18
South Essex	343.32	-0.38	228.97	5.40	-23.31	-4.77
South West Lakes	681.68	0.32	775.88	9.01	-1.85	-0.90
Tees	74.81	-0.94	-206.55	2.97	-44.86	-8.78
Teme	268.26	-0.56	99.97	4.81	-31.89	-6.41
Till	283.43	-0.53	124.01	4.80	-29.94	-6.02
Trent Valley Staffordshire	261.04	-0.55	98.51	5.10	-32.04	-6.48
Tweed	165.31	-0.75	-57.94	3.15	-36.92	-7.22
Tyne	683.79	0.29	770.77	8.95	-1.91	-0.90
Upper Mersey	694.76	0.35	799.01	9.29	-0.70	-0.72
Waver or Wampool	373.58	-0.27	292.78	5.81	-22.52	-4.67
Wear	357.71	-0.39	241.77	5.73	-25.94	-5.31
Wey	293.66	-0.54	132.95	5.08	-30.80	-6.20
Wyre	585.88	0.14	627.43	8.28	-8.60	-2.17

Values expressed on a 'per hectare of land displaced' basis

Table 8-6 EAgRET results for individual WMCs that were not originally growing maize for: AD.

WMC	N Balance (kg ha^{-1})	P Balance (kg ha^{-1})	Abiotic Resource Use (kg ha^{-1} Sbe)	N Fert (kg ha^{-1})	P Fert (kg ha^{-1})
Adur and Ouse	-120.81	-28.88	2.11	-32.05	15.14
Aire and Calder	-140.74	-38.74	3.27	-13.54	18.00
Alt and Crossens	-88.16	-21.70	0.07	-55.63	4.03
Arun and Western Streams	-119.75	-28.91	1.69	-41.28	12.52
Avon Bristol and North Somerset Streams	-129.06	-31.28	2.16	-35.47	15.29
Avon Hampshire	-107.45	-22.30	1.15	-47.45	12.62
Cuckmere and Pevensey Levels	-132.18	-34.13	2.84	-20.52	17.21
Darent	-111.76	-22.20	0.96	-56.28	11.94
Dee	-138.38	-34.26	2.28	-37.15	15.56
Derwent Derbyshire	-140.02	-38.32	3.31	-12.94	18.40
Derwent North West	-64.92	-16.59	1.12	-15.77	7.76
Douglas	-131.00	-34.73	2.70	-22.92	16.03
Dove	-144.04	-39.60	3.44	-13.18	18.70
East Hampshire	-110.35	-24.36	1.31	-41.94	12.94
Eden and Esk	-130.90	-34.85	2.69	-21.34	16.45
Esk and Coast	-129.46	-33.50	2.67	-23.52	16.43
Hull and East Riding	-87.26	-11.48	-0.69	-83.42	6.04
Irwell	-151.28	-44.64	4.35	6.05	21.31
Kennet	-100.24	-19.20	0.65	-52.56	11.04
Kent and Leven	-147.07	-42.70	4.03	0.82	20.28
Loddon	-131.73	-32.62	1.80	-43.63	13.02
London	-116.17	-27.28	2.02	-29.34	14.85
Lower Thames	-112.17	-21.64	0.91	-54.38	12.05
Lune	-148.32	-42.89	3.92	-2.61	19.80
Mersey Estuary	-110.31	-26.19	1.58	-37.64	12.80
Mole	-120.22	-28.33	1.90	-36.46	14.25
North Cornwall, Seaton, Looe and Fowey	-127.80	-33.10	2.33	-28.59	15.20
Northumberland Rivers	-121.17	-28.93	1.99	-35.97	14.46
Ribble	-150.10	-43.38	4.10	0.25	20.63

Table 8-6: Continued					
WMC	N Balance (kg ha^{-1})	P Balance (kg ha^{-1})	Abiotic Resource Use (kg ha^{-1} Sbe)	N Fert (kg ha^{-1})	P Fert (kg ha^{-1})
Roding, Beam and Ingrebourne	-96.94	-14.81	-0.25	-68.42	8.34
Rother	-121.37	-28.14	1.87	-32.94	14.41
Soar	-117.44	-24.82	1.43	-49.95	13.22
South Devon	-128.72	-33.27	2.44	-27.40	15.63
South Essex	-124.82	-28.96	2.06	-30.69	15.47
South West Lakes	-140.32	-39.36	3.41	-9.29	18.56
Tees	-111.15	-23.09	1.06	-53.01	11.76
Teme	-119.56	-28.07	1.84	-39.82	13.63
Till	-115.85	-26.94	1.80	-37.56	13.82
Trent Valley Staffordshire	-125.65	-29.87	1.94	-40.38	14.19
Tweed	-102.33	-21.74	1.12	-43.95	12.08
Tyne	-137.01	-37.77	3.41	-9.33	18.60
Upper Mersey	-143.65	-41.19	3.56	-8.33	18.27
Waver or Wampool	-123.44	-31.54	2.13	-29.98	14.76
Wear	-123.49	-29.87	2.11	-33.78	14.92
Wey	-121.97	-28.13	1.90	-38.73	14.33
Wyre	-140.95	-38.15	3.19	-16.47	17.99

9 Appendix 3: Case studies

9.1 Case Study 1: Crop only digester of at least 1 MW in size

Plant location and ownership

This case study is based on a plant run by a commercial operator in the renewables sector. The plant is based in the East of England and was commissioned in 2013, producing 2.2-2.4 MW electricity for the national grid. The plant uses 33k tonnes of feedstock per annum which is comprised of 97% maize with small amounts of hybrid rye, grass and energy sugar beet. The output is combined heat and power (CHP).

All feedstock for the plant is supplied by a local grower group, mainly focussed on vegetable crops, which is sub-contracted to the plant owner to provide all feedstock. The grower group is responsible for sourcing land, buying seed and fertiliser, drilling and harvesting for all energy crop production.

Key stakeholders interviewed were:

- Plant owner
- Grower group
- Two farmers supplying the plant
- Two land agents familiar with AD in the area
- CLA Head of Renewable Energy
- EA National Advisor

Reasons for development and plant details

The growers group were looking for other crop options to grow on their lighter land and in particular were looking for a replacement for spring barley. This was partly due to cereal prices being low and yields poor when spring barley followed straw carrots, which is a popular system in this region. The straw applied in carrot production consumes a high level of soil nutrients which affects the following crop in the rotation. The rooting system for maize is better able to break down the straw and it yields well in rotation following carrots.

The growers group, looking for new, stable income streams, also considered producing woodchip as an alternative crop, to feed the biomass boiler located at University of East Anglia. This initiative did not come to fruition so they spent several years looking at technology providers for AD in the UK, Italy, and Germany. The plant owner agreed to work with them to finance the plant which started operations in 2013 with 229 hectares of maize. The growers group are now growing around 1,000 hectares of feedstock, mainly maize, for this plant.

Experience of AD plant operation and wider perspectives

<u>AD Activity in the local area</u>

Within a 50 mile radius there are five other plants, ranging from 1.4 to 4 MW. These plants have mostly been commissioned in the last 2-3 years. According to one local land agent, these plants are taking feedstock from roughly 4,000 hectares in total. There is currently an additional site where planning permission has been requested.

<u>Feedstocks and digestate</u>

Growers in the area have many cropping options as the land is suitable for a range of crops and there is demand from packers and processors for supplies of potatoes, sugar beet, and vegetable crops as well as for cereal crops. The choice of feedstock in this area was predominantly maize due to a combination of factors including:

- Interest in having another spring sown-crop, especially to follow carrots.
- Low prices for competing arable crops especially spring sown crops such as spring barley.
- Hybrid rye was trialled but did not yield well in the area.

Some grass is used by the plant, planted in September and harvested in May as it acts as ground cover, preventing a period of bare land.

Growers in the group receive both liquid and solid digestate free of charge but incur a charge for haulage. Digestate is returned in solid and liquid form to the maize growers in proportion to their supply of feedstock. The distribution and spreading of liquid digestate and the distribution of solid digestate is contracted out to two different grower members who have developed their own businesses to do this.

Liquid digestate can be applied to wheat, barley, maize, oilseed rape, beans and sugar beet and is spread from February to June and also in August (before drilling OSR) in accordance with NVZ regulations for open and closed periods. One farmer interviewed reported that he got the best results by applying liquid digestate before the crop is established however others applied digestate later in the growing season. According to the growers interviewed, the use of liquid digestate has resulted in a reduction in use of artificial nitrogen by 30-60kgs/ha on cereals crops saving approximately £40/ha. The solid digestate gives similar benefits to other forms of compost. Solid digestate is delivered to farm and kept in a pile until the grower is ready to spread. Spreading of solid compost is done by the growers themselves on farm.

The growers interviewed felt that the use of both solid and liquid digestate on the land was an excellent way to replace nutrients, beneficial bacteria and organic matter. Some farmers indicated that they get positive results by ploughing in digestate as well as pig manure as this ensures that the fertiliser gets directly to the roots and is especially good in drought situations.

<u>Local impacts</u>
The Growers Group is able to choose feedstock crops independently but the plant owner provides advice. Feedstock for the case study plant is all provided by the Growers Group, which is responsible for the choice of growers of feedstock, who are all located within 10 miles of the plant.

Management of the supply of feedstock is carefully controlled by the Growers Group which undertakes the fieldwork (drilling and harvesting) for growers. Drilling is concentrated into a 4-5 week period (weather permitting) and harvesting is done quickly to minimise disruption on the roads. The group coordinates with the local council to ensure the smooth movement of vehicles during harvest and evidence was presented of correspondence from the council giving positive feedback following last year's maize harvest.

Displacement of other crops
None of the growers interviewed had taken on extra land to produce maize so all were substituting maize for another crop in the rotation. Based on evidence from the farmers and land agents interviewed, maize has replaced wheat, spring barley, potatoes, and sugar beet in arable rotations and has been useful in weed control in areas with pernicious blackgrass. The head of grower group indicated that British Sugar had cut back beet requirements for local processing facility by 20% in 2014 of which, some of the land was put into maize production for the plant.

Example rotation 1: wheat, rape, wheat, maize, wheat, peas, wheat, sugar beet

Example rotation 2: potatoes, wheat, sugar beet, spring barley/wheat, rape, wheat, maize, potatoes

The farmers interviewed were predominantly arable growers although one also produced pigs and let some land for sheep grazing. These operations did not appear to be affected by the addition of maize production.

Land rental impacts

The plant owner uses two types of rental agreements for their plants:

1. payment on a £/t basis for maize supplied
2. payment of £ per hectare for land plus a yield bonus

All growers interviewed from the Grower Group were paid on a pounds per tonne basis for their maize which is taken directly from the harvester to the AD plant. Payments in 2014 were £33/t (fresh weight basis at 32% dry matter) with average yields of 50t/ha. To supply the plant, growers must commit to a minimum of 12 ha of maize, pay a management fee of £100/ha and supply for a minimum of 5 years (though they don't have to supply each year). Additional annual costs include £135/ha for seed, £50/ha for fertiliser (DAP) and £45/ha for drilling.

All stakeholders were asked to give their views on the impact the increase in maize production has had on land rental values locally:

- Growers Group: Most growers supplying the plant are growing on owned land or on land farmed within contract farming agreements as part of their arable rotation. The general view is that growing maize for AD has not had much effect on rental values; instead they felt that commodity prices have the greatest impact on rental values. The group expect that a higher proportion of farmers supplying other AD plants in the area are growing maize on rented land.

- Farmers: Supplying farmers feel that the case study AD plant has had some localised effect on land rental values near to the plant. Other crops putting pressure on land rental values are potatoes, sugar beet and vegetable crops. Rental rates for Farm Business Tenancies (FBT) have increased £50-60/ac in the last 5 years and one farmer indicated that the AD plant owner was paying £140/ac rent for non-irrigated land near the plant. It is difficult to separate the impact arising from different factors, with big players in the fresh produce market encouraging potato growers to pay high land rental prices. FBT grade 2 un-irrigated land rental prices are around £270/ac, up from £200/ac over the last 5 years.

- Land agents: In addition to competing crops (sugar beet, potatoes and vegetables), upward pressure on rental values is caused by outdoor pigs, solar energy generation and land acquisition for development. AD has added to those pressures on land use and for farmers to consider paying higher land rents. Agricultural Holding Act Tenancy (AHT) rates are £80-90/ac depending on the local residential market but there are fewer and fewer of these arrangements left. FBT rental rates vary widely in the range of £120-290/ac. With irrigation water, this would add £150/ac on top. One land agent said he would expect to see higher FBT rents near to AD plants.

- Stakeholder (CLA): The CLA does not think there is much energy feedstock grown on rented land in the eastern region, as most feedstock is grown on owned land or in contract farming agreements. It represents a good option for arable growers to extend rotations and in some situations helps growers to satisfy the Common Agricultural Policy (CAP) 3-crop rule.

Economic Impacts

Economics of the plant

The AD plant represented an investment of £7-8 million and has secured employment for 4 full time staff and 33 seasonal workers. Two grower members managing independent digestate spreading businesses also benefit through annual contracts with the plant.

In terms of community engagement, the plant has had visits from the Parish Council, Rotary Club, local college and local farmers groups.

The crop has generally replaced winter wheat and winter and spring barley in arable rotations. In terms of returns, there have been some savings on artificial fertiliser costs from use of liquid digestate; this can reduce artificial nitrogen applied by 60kgs/ha. One famer quoted total N applied for maize to be 120kgs, wheat 200kg winter barley 180kgs. The digestate can replace a significant proportion of artificial N for any of these crops. As drilling and harvesting is done by the Growers Group, no extra labour is needed on farm and there is no requirement for changes in equipment. The costs of road cleaning following maize harvest were paid through the farmers' service fee to the plant. The service fee is £100/ha to become a member of the growing group; this is refundable after 5 years or when the farmer leaves. Growers commit a minimum of 12ha of maize to the group, which contributes to the total tonnage needed to supply the plant. Table 9-1 summarises annual costs provided by one of the case study farmers.

Table 9-1 Annual fees for farmers contracted to grow maize

Drilling	£45/ha
Seed	£135/ha
Fertiliser	£50/ha
Haulage (of feedstock to the plant)	£35/ hour
Haulage (of digestate to the farm)	£35/ hour

Overall, gross margins for maize as quoted by growers in Table 9-2 compare well to the arable crops maize replaced in the rotation and this was noted as a direct economic benefit. Also, members of the grower group felt that having a new crop with less volatile price movement due to multi-year pricing arrangements with the plant owner gives welcome stability for farm returns.

Table 9-2 Crop gross margins estimated by case study farmers for maize and displaced crops

	Gross margin (£/ha)			
	Maize	**Feed wheat**	**Feed barley**	**Sugar beet**
Farmer 1	£640	£575	£500	N/A
Farmer 2	£824	£550	N/A	£1,950

Table 9-3 shows an example cost calculation comparing maize grown as AD feedstock (@£33/t) and feed wheat production in an average year where the farmer achieved 8.5t/ha for feed wheat (@£130/t). Winter wheat or barley yield increases of up to 15% were reported where maize was harvested promptly in October allowing drilling to take place immediately. The value of digestate is estimated at £135/hectare of forage maize fed to the AD plant based on a yield of 45t/ha and a value of £4.50/m3 of digestate quoted by Growers Group.

Table 9-3 summarises gross margin data estimated by the Growers Group. This gives an idea of the economic benefits of growing maize. The calculation is simplified and other considerations, for example additional growing costs, the net value of digestate and any increase in yield to the following crop in the rotation would need to be considered for a full economic comparison.

Table 9-3 Detailed gross margins for maize and displaced crops, not allowing for wider benefits

	Maize	**Winter wheat**
Yield (t/ha)	*45*	*8.5*
Crop price (£/t)	*£33*	*£130*
Crop sales (£/ha)	1,485	1,105
Total Output	**1,485**	**1,105**
Seed (£/ha)	165	55
Fertiliser (£/ha)	300	255
Sprays (£/ha)	100	220
Total variable costs (£/ha)	**565**	**530**
Gross Margin (£/ha)	**920**	**575**

These broad gross margin calculations highlight an economic advantage for maize over winter wheat but this is very sensitive to wheat price; winter wheat would be competitive if prices were £10-40/t higher than the £130 used in the budgets. The price of feed wheat at the time of the interviews was £110/ tonne.

Wider economic impacts

Farmers and land agents noted several indirect economic effects. An improvement in wheat yields resulting from the elimination of blackgrass in wheat production was the most important effect noted. This benefit is also seen as reduced use of both herbicides and fungicides over the longer term. Farmers were hoping that the reduced incidence of blackgrass would also reduce disease pressure in wheat crops.

A further indirect benefit reported is improved utilisation of the farm workforce and machinery as maize fieldwork occurs in May, allowing for reduced hours for those hectares in March/April, which is a typically a busy time for other field work. For one farmer interviewed, maize production allowed him to spread pig muck over a longer period of time across the season, resulting in a savings in muck storage costs.

Environmental impact

All farmers interviewed felt that on balance, producing maize in sensible rotation on flat and relatively light land had an overall positive impact on the environment. The key environmental themes are considered in turn below.

Soil erosion, quality and structure

The Grower Group and farmers commented that soil erosion is unchanged or slightly increased on maize crops as it is grown on flat land, not on heavy land and due to regular advisory input from the Maize Growers Association (MGA) on best practice. However, the nature of the crop leaves more exposed soil, which is a risk, although rolling helps reduce that. Other stakeholders (EA, CLA, and land agents) report that if farmers follow best practice guidelines this should not be a problem; good practice is now included in cross compliance as per Soil Protection Standards 2015.

Farmers and stakeholders are aware of the potential for increased soil erosion due to the late season harvest date leading to bare land during winter. To mitigate against this, the Growers Group together with the AD plant owner are trialling various cover crops as discussed above with a view to avoiding bare land over winter. Farmers also were aware that maize is a "hungry" crop with the potential to deplete soil nutrition. Regular meetings are held with the MGA where advice is given on best practice for seed bed preparation, cultivation, input use etc.

Farmers interviewed felt that spreading digestate in rotation has provided valuable nutrients and organic matter to the soil, leading to higher crop yields and lower fertiliser input costs. Stakeholders also commented that digestate has benefits in introducing organic matter to soils and more work could be done on valuing digestate for its nutrient content.

<u>Water quality</u>
The Growers Group and farmers could not comment on water quality impacts but other stakeholders reported that the impact is the same as with other arable crops, no more or less. There could be problems with increased phosphate in water but it is not clear that this can be attributed solely to maize.

Management techniques that are being trialled to mitigate against any negative impacts include:

- Sow grass seed a few months after maize is sown to stabilise soil. Maize is harvested leaving established grass sward for later harvest and potential use as second AD feedstock
- Spread digestate together with radish seed as a cover crop which his then ploughed in
- Using grass margins to reduce run-off
- Undertake an Environmental Impact Assessment of AD plants

<u>Biodiversity</u>
Growers did not feel that there was a biodiversity impact of including maize in the rotation; stubble from the previous year's crop provides habitat over winter before maize is drilled although the standing crop is not great for birds. Most were in ELS and some have HLS agreements with pollen and nectar seed options often chosen to provide cover for birds. The Big Farmland Bird count indicated good results locally.

<u>Climate change</u>
Stakeholders reported that as maize is not direct drilled, ploughing leads to higher GHG emissions, although some growers are beginning to try direct drilling. It is the plant owner's policy aim to have zero fugitive emissions from all of their AD plants. The plant owners regularly check plants for leaks using thermal image cameras and try to minimise methane escape.

Summary of opportunities and risks
Farmers and stakeholders interviewed in the East of England felt that on balance maize was a good crop for the area as it fits well into rotations. There is both an economic and agronomic benefit. Some growers indicated that they achieved yield increases of up to 15% for winter wheat and winter barley when these crops followed maize. Excellent maize yields were achieved when maize followed carrots. While maize competes with existing crops in the rotation, these are in turn affected by markets and policy changes. For example in this region, British Sugar has cut back requirements to supply the local processing plant by 20%. In contrast, maize production for AD provides a stable income due to the multi-year agreements in place and provides favourable gross margins, especially when commodity prices are low.

Given the dynamic cropping situation and wider policy drivers, the impact of maize for AD on land rental prices is difficult to gauge accurately. However, it is likely that at a local scale it provides additional competition for rented land and will increase rental values.

The AD plant owner has taken care to consider the potential environmental problems associated with growing maize and has implemented receive regular advice from the MGA to manage issues of soil nutrient depletion, soil erosion and run off. Some stakeholders indicated that maize production in the area had a positive impact on soils locally where maize has displaced root crops as it is less damaging to soil structure and results in less soil compaction problems.

9.2 Case Study 2: Crop only digester of at least 1 MW in size

Plant location and ownership

This case study is based on a biogas plant run by a farmer-owner operator. The plant is based in the East of England and was commissioned in 2012, producing 1.4 MW electricity. The plant uses 24k tonnes of feedstock per annum which is comprised of 12k tonnes maize, 8k tonnes whole crop rye and 4k tonnes grass silage. Wet sugar beet pulp has also been used in the past. The output is combined heat and power (CHP).

The AD plant is run as a joint venture partnership between two farmers with one contracted to supply all the feedstock. In addition to feedstock grown on the owner-operator's farm, up to 11 local farms supply the plant.

The owner-operator of the plant was not prepared to share farmer suppliers' contact details so farmers supplying another AD plant with similar criteria in the region were interviewed instead.

Key stakeholders interviewed were:

- Plant owner-operator who is also supplying feedstock
- Three farmers supplying a similar plant in the region
- One land agent familiar with AD in the area
- CLA Head of Renewable Energy
- EA Advisor Eastern Region

Reasons for development and plant details

Several reasons were given by the plant owner for the development of the AD plant, including diversifying the farm business, providing fuel security for an existing on-farm business park and for the generation of "green" electricity. The owner-operator is committed to renewable energy both for ethical and reputational reasons. The plant also provides an additional outlet for break crops that are grown in the area allowing farmers to benefit from longer arable rotations and the feedstock crops serve as a tool in the control of blackgrass and other arable weeds.

The owner-operator financed the plant which cost £5 million to build with grant support from the Rural Development Programme for England (RDPE) of £750k. The plant was commissioned in 2012 and is eligible for Renewable Obligation Certificates (ROCs) for generation of electricity. For every megawatt (MW) of electricity generated, the operator receives 2 ROCs (valued at £79 on the day of the interview in March 2014).

Experience of AD plant operation and wider perspectives

AD Activity in the local area

Within a 60 mile radius there are four other AD plants ranging from 1.0 to 3.5 MW, which have mostly been commissioned in the last 2-3 years. While maize is used by some of these plants, vegetable, fruit and food manufacturing waste is widely used as feedstock for all but one of these plants.

Feedstocks and digestate

The feedstocks used by the case study plant include maize, whole crop rye, grass silage and in some limited situations, blackgrass-infested whole crop wheat and sugar beet pulp. Maize was chosen as a feedstock due to favourable growing conditions on the light soils in the region and for the extended rotational opportunity offered by another spring sown cereal (following maize). Hybrid rye was noted as an excellent crop option for heavy land.

In addition to these feedstocks, farmers interviewed were supplying sugar beet to the second plant. This crop grows well on the light land in the area and the proximity to the sugar beet processing facilities means that farmers in the area are experienced in growing sugar beet.

Farmers interviewed said that including maize in arable rotations has had a beneficial impact on other crops such as wheat. One farmer said "*wheat is an important crop and a driver for arable rotations in the area so anything that improves wheat yields and eases production is favoured*." Maize harvested in October can lead to good soil conditions for winter wheat to be planted. Other reasons cited for growing maize include a higher gross margin (relative to other arable crops) and control of volunteer potatoes and blackgrass in the rotation.

Only one of the farmers interviewed was using digestate on their crops. This was because the second plant was not operating at full capacity so only limited quantities of digestate were available. Farmers supplying the second plant were expecting they would receive 80% of the tonnage of feedstock supplied back as solid digestate and expected to have to pay haulage costs. One farmer said he did not expect that the solid digestate would reduce his needs for artificial fertiliser as nitrogen levels were low but expected the benefits of this product would be increased soil organic matter. For the liquid digestate which was expected to give greater benefits in increased nitrogen, farmers would have to pay £3/t plus haulage costs.

According to the farmer using liquid digestate on his crops, he expected a 50% cost saving could be achieved on the crop treated by replacing some artificial fertiliser with digestate. Other farmers were using compost or turkey muck to replace artificial fertiliser.

For the case study plant, farmers are able to buy back separated solid digestate (10 tonnes per hectare grown) at a price of £6 per tonne ex-AD plant. No haulage costs were provided.

Local impacts

The owner-operator sources feedstock crops from a number of farmers who are all located within 10 miles of the plant. For the case study plant, farmer suppliers are responsible for all cultivation, drilling and spraying for maize production while a contractor manages maize harvesting for suppliers.

Farmers supplying the second plant expressed some concerns about impacts on the wider community due to vehicle movement and safety during maize harvest. They are currently investigating, through their feed suppliers group, the possibility of switching to lorries rather than using tractor/trailers for haulage to the plant at harvest.

Displacement of other crops

None of the farmers interviewed had taken on extra land to produce maize; all were substituting maize for another crop within the rotation. Based on the evidence from the farmers and land agents interviewed, maize has replaced wheat (especially second wheat), spring barley, sugar beet, oilseed rape (OSR) and carrots in their rotations and has been useful in weed control and in some situations leads to improved yields on crops following maize. All the farmer growers interviewed were arable farmers although some with other activities such as managing a grain store.

*Example rotation 1: wheat-winter barley-OSR-wheat-**maize**-wheat*

*Example rotation 2: wheat-sugar beet-spring barley-**whole crop rye**-OSR-wheat*

*Example rotation 3: wheat-barley-wheat-sugar beet-**maize***

Low sugar prices offered by British Sugar has given added incentive to local farmers to find an alternative outlet for sugar beet, which works well in arable rotations. Recently farmers in the local sugar beet grower group decided to take a 50% "holiday" from supplying beet for the sugar plant, allowing this beet to be used by the AD plant without jeopardising their quota requirements. One of the benefits of growing rye is that it is harvested in mid-June which allows for timely sowing and establishment of OSR.

Land rental impacts

All stakeholders were asked to give their views on the impact the increase in maize production has had on land rental values locally:

- <u>Owner-operator</u>: Most growers supplying the plant are growing on owned land or on land farmed within contract farming agreements as part of their arable rotation. Land rental values in the area are high due to competing uses of the land, including for growing sugar beet, carrots, onions and potatoes. Rental values have gone up as some farmers are prepared to pay over the market value to expand operations.

- <u>Farmers</u>: Supplying farmers do not think that there is enough feedstock grown locally to influence land rental values. Also, the lack of livestock in the area means that there is not the same level of competition for land for forage crops. Other crops putting pressure on land rental values are sugar beet, potatoes and vegetable crops. Rental rates for Farm Business Tenancies (FBTs) have increased from £120 to £150/ac in the last 5 years. Farmers interviewed feel that commodity prices have the greatest influence on land rental values.

- <u>Land agent</u>: As maize is not used in all of the large AD plants in the local area, the area of maize production in the county is still modest so the land agent does not think there has been any impact on land rental rates. FBT rental rates for grade 3 arable land are in the range of £150-175/ac; with irrigation water, rates are £200/ac. In areas with a high concentration of large AD plants, AD feedstock production may have set a floor on rental values but this is not the case locally.

- <u>Stakeholder (CLA)</u>: The CLA does not think there is much energy feedstock grown on rented land in the eastern region, as most is grown on owned land or in contract farming agreements. Maize represents a good option for arable growers to extend rotations.

Economic Impacts

Economics of the plant

The AD plant represented an investment of £5 million and has secured employment for 3 full-time employees: a site operator, an administrator and an additional member of the arable staff responsible for digestate irrigation, movement and spreading. One contractor has also benefited by additional opportunities to harvest maize from farms supplying the case study plant.

Economics of feedstock production

Growers to both plants were paid on a per tonne basis (fresh weight basis at 32% dry matter) for their maize. Growers interviewed supplying the second plant were paid £29 per tonne for maize and growers to the case study plant were paid £30/t for maize and rye. Haulage costs were not given by the farmers.

Yields of growers supplying the case study plant have averaged 44t/ha since the first harvest in 2011. The plant operator felt that these yields were somewhat low as the first priority is to establish first wheat so early maturing/lower yielding maize varieties are grown. Whole rotation gross margins are considered more important than individual crop gross margins.

Only one farmer interviewed was using digestate which he indicated offered savings on artificial fertiliser costs. This farmer suggested that he could replace all 120kgs/ha of artificial fertiliser required for maize with digestate. Total nitrogen (N) noted as required by this farmer for other crops was as follows:

- rye 150kgs/ha
- spring barley 100-120kgs/ha
- wheat 220kgs/ha
- OSR 240kgs/ha.

Other farmers who were interviewed did not use digestate as the AD plant was under capacity and not supplying much digestate. Furthermore the other farmers had arrangements to receive other waste material to use as compost.

Cultivation, drilling and spraying is done independently by the farmers and harvesting is done by the plant operator's contractor. Farmers interviewed indicated that no extra labour was needed on farm and there was no requirement for additional equipment.

One farmer indicated that he had been spending £100/ha on blackgrass control before he started growing feedstocks for AD and was hopeful that he would be able to save some of this cost by widening his rotation with maize production.

Overall, gross margins for maize as supplied by case study farmers compare well to the arable crops maize replaced in the rotation and this was noted as a direct economic benefit. Also, having a new crop with less volatile price movement due to multi-year pricing arrangements with the plant owner gives welcome stability to a portion of farm returns. Gross margins are shown in Table 9-4 below for one of the case study farmers over two harvests.

Table 9-4 Crop gross margins from maize and displaced crops estimated by a case study farmer

	Gross margin £/ha				
	Maize	**Spring Barley**	**Sugar beet**	**Energy Beet**	**Rye**
2014	870	627	1,110	1,235	618
2015	552	494	-	-	-

A further cost estimate for one farmer's 2015 harvest is shown in Table 9-5, comparing maize grown as AD feedstock (@£29/t) and spring barley production in an average year where the farmer expects to achieve a yield of 6.8t/ha for spring barley (@£125/t). The farmer in this example did not share haulage fees and did not incur any management fees and did not use digestate. The gross margin calculations below show a small economic advantage for maize in 2015 compared with spring barley but reports that there was a much greater economic advantage in 2014 due to better maize yields and prices that year. The farmer commented that the value of fertiliser applied was relatively high for a forage maize crop as they are trying to maximise the yield for energy production, which wouldn't be such a priority if used for fodder.

Table 9-5 Detailed gross margins for maize and displaced crop per hectare.

	Maize	**Spring Barley**
Yield (t/ha)	*39.50*	*6.8*
Crop price (£/t)	*£29*	*£125*
Crop sales (£/ha)	1145	850
Total Output	**1145**	**850**
Seed (£/ha)	60	70
Fertiliser (£/ha)	270	190
Sprays (£/ha)	54	86
Total variable costs (£/ha)	**384**	**346**
Gross Margin (£/ha)	**761**	**504**

Wider economic impacts

Several indirect economic benefits of producing maize feedstock were reported by farmers supplying another AD plant and stakeholders. One farmer commented that supplying maize and sugar beet under a 10 year agreement has provided long term economic stability to his business. A further indirect benefit is improved utilisation of the farm workforce and machinery as maize fieldwork occurs in May, allowing for reduced hours for those hectares in March/April, which is a typically a busy time for other fieldwork. Some savings were reported for combine use in situations where maize is harvested by contractors. For one farmer, producing maize on light land in dry years yielded better than other arable crops on the same land. Weed and disease control and improved yields for wheat and OSR following maize were also noted as contributing to improved farm income.

Farmers who were not currently receiving digestate felt that use of this product would be beneficial especially for light, sandy soils due to the addition of organic matter to the soil.

Some farmers noted that feedstock production can help to satisfy the requirements of the CAP 3-crop rule.

Environmental impact

Farmers interviewed felt that producing maize in arable rotations on light land had an overall positive impact on the environment. The key environmental themes are outlined below.

Soil erosion, quality and structure

Farmers are aware of the potential environmental problems associated with growing maize, including the fact that late season harvest leaves bare land over winter, increasing the potential for erosion. To mitigate against this, one local land agent described the practice of planting kale or beans in October following the maize harvest. These cover crops are ploughed in if a spring crop is to follow, giving both soil nutritional benefits as well as erosion control.

Some farmers described using low impact tyres to minimise soil compaction. Farmers also noted that they try to harvest maize as early as possible and not in wet conditions to preserve soil structure. Some use crawler equipment which runs on a track instead of tyres to minimise soil compaction.

Farmers were aware of the benefits to soil nutrition of spreading digestate in rotation; however, only one farmer interviewed was using digestate. The others expected that digestate would be made available to them in future years. Some farmers had access to other forms of compost and turkey manure which provided valuable nutrients and organic matter.

Water quality

Farmers were unsure about water quality impacts but thought that as long as the application of agri-chemicals was managed appropriately that there should not be any problems. One thought that the local water company would be checking and that if there were problems they would be alerted.

One stakeholder reported an AD plant related pollution incident that was being investigated in the region. This occurred as a result of harvested maize being stored in clamps on an unsuitable site where excellent drainage systems meant that effluent from the maize was allegedly entering local groundwater sources. This stakeholder expressed concerns that maize only AD plants were not required to seek full environmental permitting but only planning permission for AD plant installation. The storage of maize on unsuitable areas was occurring in situations where AD plant developers had faced delays in obtaining planning permission but had contracted with farmers to supply maize. Other concerns noted included feedstock "creep" where plants registered to take maize-only had evolved to use poultry manure and sugar beet pulp, which would require more stringent environmental permitting. There was some speculation that there might be a move to require maize-only plants to have an environmental permit.

Biodiversity

Famers felt there were both benefits and costs to wildlife of producing maize in the rotation. One felt that the disruption to ground nesting birds was less with maize than with other arable crops, but that the canopy for maize is thicker so birds will nest for a shorter time as conditions on the ground below were too dark. All but one of the farmers were in ELS and several were also participating in HLS though there were no options directly applied to the area of maize production.

Climate change

The case study AD plant was receiving ROC payments and therefore to be eligible for these payments was required to provide information on the sustainability of plant operations and feedstock suppliers. The plant operator did not provide this information but reported that he understood that this year there would be additional requirements for plant operators to complete a sustainability matrix though he did not have this information to share.

One farmer was direct drilling maize which he thought reduced his GHG emissions both from the soil as well as resulting from reduced use of diesel.

Summary of opportunities and risks

Farmers and stakeholders interviewed in the East of England felt that maize offered an excellent opportunity to widen the range of crop diversity while giving added stability to farm income as a result of multi-year agreements offered by plant operators. Maize was a good crop for the area as it fits well into rotations and has given some growers an alternative outlet for sugar beet. For some farmers, maize has helped to satisfy the requirements of the CAP 3-crop rule.

Farmers cited both economic and agronomic benefits. Some farmers indicated that they achieved yield increases of up to 10% for wheat and barley when these crops followed maize; however, other farmers reported no yield increases. Maize provides favourable gross margins compared to other arable crops, especially when commodity prices are low. Reduced costs for herbicides and artificial fertilisers also contribute to positive returns.

The case study AD plant owner is required to address environmental problems associated with growing maize through the Renewable Obligation Certificate scheme. Farmers and stakeholders showed good awareness of the environmental risks of growing maize but felt that these risks were no greater than for other arable crops. Some farmers are using cover crops to reduce the soil related risks of maize by limiting areas of bare land over winter and for their nutritional benefits.

The potential for effluent from maize stored on unsuitable sites to contaminate local groundwater was identified as a risk of maize production in the area.

9.3 Case Study 3: Mixed agricultural feedstock digester of at least 140 kW in size

Plant location and ownership

This case study relates to a 2MW farmer-run AD plant in the West Midlands that utilises a mixed feedstock of waste and crop feedstock. The plant is owned and run by the case study farmer. The farm extends to 657 hectares, 405 hectares of which is owned with 252 hectares of continuous annual rental agreements and FBTs. Farm enterprises include six feedstock crops for the AD plant and short term grassland and stubble turnips for over-winter sheep grazing. The farm is mainly arable with 40 hectares of land used to graze sheep and has a Higher Level Stewardship Agreement. The arable crops are:

Crop	Amount grown (hectares)
Wheat	182
Oilseed Rape	121
Maize	142
Hybrid Rye	101
Fodder Beet	40
Triticale	30

The farmer who owns the AD plant was interviewed for this case study and will be referred to as the case study farmer throughout this section. Other local key stakeholders interviewed included the County Council, Environment Agency, a local land agent and the National Farmers Union (Area Advisor).

Reasons for development and plant details

The case study farm developed the AD plant for a number of economic reasons. The case study farmer was particularly concerned about the volatile food commodity markets; wheat was selling for a cost lower than the cost of production, the dairy market was volatile (which subsequently led to the farmer leaving the market) and potatoes were becoming an increasing risk to grow. Subsequently the all-arable system was then impacted as the cereal price dropped below cost of production and the local sugar beet factory closed (freeing 16,000 hectares of sugar beet land in the local area). Additionally, the case study farmer had concerns about a reduction in the Single Farm Payment which he believed could be uncertain in the future. Government was encouraging renewable energy development on farm and this seems an important opportunity for the business.

By introducing an AD system the farmer believed that the business could move to a more sustainable and traditional mixed farming system. Both the variety of crops grown and the number of livestock kept has increased while spring cropping has increased. Furthermore, it is felt that the use of digestate has improved the fertility and structure of the soil. Most importantly, it was thought that the AD plant would provide an additional income stream and reduce exposure to market volatility.

The NFU believes the main drivers for the investment in AD systems are the financial benefits and ease slurry and manure management. The latter is particularly important for larger dairy farmers. However, the NFU stated that the majority of dairy farmers that would benefit for AD systems to manage waste do not have the capital to invest in the technology. Within the region, it is believed that arable farmers are investing because of low and volatile cereal prices and, compared to similar sized dairy units, have larger resources of capital for investment.

The AD plant was built in 2012 and is a semi-plug flow digester that consists of 2 Combined Heat and Power (CPH) units – 500 kW and 800kW – that are designed to have a potential capacity of 1300kW/hr. Current production levels are 1176 kw/hr, which has exceed the initial design.

Experience of AD plant operation and wider perspectives

<u>AD Activity in the local area</u>

The case study area is a "hub" of AD activity with two separate AD technology companies based in the county. This has resulted in a high level of AD development throughout the West Midlands. In addition to this, there has been an increase in the supply chain associated with AD development. Interviewees estimate that there are 20 AD plants within the case study county; 13 permitted with a further 7 in the progress of being permitted. This trend in increasing AD activity has been within the last 5-7 years.

The case study farmer suggested that a "*saturation*" of the case study county was "*a long way away and would never be reached*". This is because a high proportion of the plants operating in the area are farm based and are largely self-sufficient. The farms are predominately medium-sized, family arable farms responding to the volatile cereal prices. In addition, some AD plants in the area are importing poultry manure as a waste feedstock. The EA has some concerns over the planning permission process and has seen a trend in permissions being given for AD plants that emphasise the use of poultry litter which subsequently move to a maize-only system.

<u>Feedstocks and digestate</u>

The feedstock for the plant consists of 58% waste mix (whey and chicken muck) and 42% crop mix (maize, fodder beet, grass and hybrid rye). The waste products are sourced locally where there is a surplus of these commodities which are typically spread to land. Poultry manure can sometimes be spread in high pollution risk conditions to manage waste quantities.

The majority of the energy crops are grown on farm, and although the case study farm does "*work with immediate neighbours in a small way to supply maize and beet*", it is in the process of reducing this reliance. In 2014 all maize was grown on farm, although the farm is regularly offered land for feedstock from neighbouring farms that are struggling with current cereal and milk markets. Some 1,800 tonnes of fodder beet was contracted to a local farmer and some hybrid rye was grown on a neighbour's land. The farmer uses an experienced independent agronomist to oversee decisions on farm and provide advice and recommendations on farm and crop management. The energy crops are grown in a 4-year rotation with other cereals. Wheat is sown after maize to manage soil erosion, this is discussed further in the following sections.

The AD plant is flexible in terms of inputs and the farmer is decreasing the amount of maize grown as an energy source for the plant (currently just less than 25% of total feedstock by weight) as it is not always a consistent material and there is a short window to harvest the maize in autumn. The ambition is to reduce the energy crop area and replace this feedstock with by-products. However, the restrictions and waste permitting rules make this transition difficult. The EA believe the permits are important to ensure waste is properly regulated. Food waste used in plants for digestate introduces a higher risk and there are no signs currently of these permits changing in the near future.

All digestate produced is used on the farm using umbilical spreading and the farmer reports improved soil health and structure which have given an increase in yields, whilst decreasing the man-made fertiliser by approximately 50 percent. Before spreading, the digestate is tested and applied strictly to crop requirements and the limits set out in the RB209 fertiliser manual.

Other positives about the digestate were noted by the NFU interviewee who argues that it is also good for controlling diseases in poultry muck such as botulism, which would not be killed if the manure was spread straight onto the farms. The EA are aware of situations where digestate tanks have failed, leaving the possibility of digestate going into roads and rivers, but this is not a regular occurrence. The County Council think that there could be problems if digestate is spread at the wrong time or in the wrong concentrations, however they believe it offers a benefit as a fertiliser.

Other impacts

During the planning stages of the AD development, the case study farm encountered some objections which the farmer felt were a result of misinformation and misdirection. Since the plant has been operational, there have been very few complaints. This opinion was reflected by the NFU who stated that a lot of the concerns expressed are unrelated to AD schemes. They said that in some instances, the public associates AD schemes with the associated pollution (odour) of pig and poultry units. However, the EA stated that there had been complaints including issues with haulage.

Displacement of other crops

Case study farm

Prior to the development of the AD plant the farm has significantly reduced its area. This coincided with the farm coming out of potatoes, sugar beet and dairying (*c*. 150 head of cattle). The land area reduced from 737 ha to the 657 ha, the area farmed presently. These changes cannot be attributed to the AD development as the reduction in the amount of land rented was driven by other economic factors.

However, since the development of the AD plant, the farm has displaced some sugar beet and mono-cropping winter cereals with spring cereals. The high number of crops within the rotation also encourages a more traditional "rural mosaic" that has associated environmental benefits. The amount of land under the HLS agreement has also increased. One of the main driver for these changes was to reduce the businesses exposure to market volatility to provide a consistent farm income through AD.

Regional trends

At a landscape level the NFU do not believe it is changing the production of other crops. Within the area the AD plants locally have access to a large range of feedstock crops, i.e. the plants are not reliant on maize, and therefore the cropping area is remaining relatively consistent.

However, the EA believe that farmers are growing more maize because it is financially more viable compared to other cash crops. In the area, the EA are aware of AD companies actively sourcing farmers for maize ground. The EA believe that within the local county there has been an increase in both maize growth and miscanthus for biomass boilers. The EA does acknowledge that the area is very mixed in its farming systems and therefore displacement is diverse. They also mentioned the closure of sugar beet factories where the land is now used for bioenergy crops; this is reflective of the case study farmer's move towards AD.

The NFU believe there is a general trend in decreasing livestock numbers, but would attribute this to other economic factors such as the milk price, and not directly to AD. The EA stated that the majority of AD plants are being commissioned in arable areas with some poultry. Therefore AD is not impacting livestock numbers within the locality.

Economic impacts

Land rental impacts

The case study farmer believes rented land in the local area is closely associated with cereal prices. An increase in rent prices for land was experienced 3 years ago. During this time period, the case study digester and one other were commissioned in the local area. However, the peak in rent also coincided with high wheat prices (£200/ tonne). During the time of high land rents, the case study farmer stated that the rent they paid for maize ground did not exceed £80 per hectare. Since this peak, rents have continued to decline. Currently the number of digesters is a lot higher yet anecdotally rents are falling. He believes local rent battles are caused by prices of different food prices, and should not all be associated with the growth of AD.

The case study farmer reports that the county has historically had a very competitive, and subsequently high, rental market. Maize for AD can be likened to other high value crops such as potatoes and carrots which made up a high proportion of the cropping in the region a few years ago. The NFU stated that a few years ago potatoes were the major driver of land rental values. The NFU also likened maize for AD to other commercial agricultural markets that fluctuate.

The land agent interviewed agreed with both of these trends. They stated that there was a price spike within the last 3-5 years and prices have decreased, particularly last year; this was also reflected by the NFU. Some AD plants were purchasing on the basis of £1.10 per 1% dry matter of material which could equate to £1500 per hectare. Currently you would expect to get maize ground for a dairy farmer at around £370 per hectare and you would expect higher rents for AD farmers, however the land agent was not able to quantify the costs. The case study farmer quoted an AD maize rental agreement at £430 per hectare over a 5 year agreement.

The NFU believe there was a lot of discussion about rental prices about 18 months ago but the main worries did not come to fruition. Furthermore they commented that rental values vary and that there is no pattern in recent local agreements.

Economics of the plant

The case study farmer was not willing to share data on the economics of the plant operation with the project due to commercial sensitivities. We were able to ascertain that capital investment was £2.8 million with no public subsidies and the plant annual turnover is £1.75 million. One of the major economic drivers was the financial savings on inorganic fertiliser, with the digestate produced by the plant applied to the farm that is in an arable rotation.

Wider economic impacts

As the farm has seen a very positive outcome from its strategic changes it has increased its interaction and financial help within the village. It has been involved with providing additional playing fields, a school building, compost for the local scouts to sell and has had several visits from groups and individuals form the local community. It intends to continue increasing this activity.

The farmer has employed two extra full time staff to run the plant. He also believes that an increase in AD plants has led to an increase in work for contractors and the ability for contractors to invest in the most up to date machinery. The NFU reiterates the case study farmer's views on increasing work for contractors and see this as a positive step for ensuring agriculture attracts people who are interested in good technology and training for sustainable farming – for examples engineers and electricians. The EA believe digesters are attracting farmers who are innovative and there are examples of innovative approaches in both digestion and digestate separation within the county. All stakeholders appreciate the increased margins for farmers who have an AD plant.

Environmental impacts

Soil erosion, quality and structure

The case study farm has many crop management systems in place to avoid soil movement and the associated concerns with water quality. Both the EA and County Council stated that where mitigation measures were implemented, the risk of soil movement and water pollution was decreased.

The case study farmer believes there is a decrease in soil erosion as maize has displaced potatoes and sugar beet. Normally wheat is sown straight after maize is harvested to manage soil loss. The farm also has a strict six-day window when harvesting maize. This is to ensure maize is harvested early, minimising the risk of poor harvesting conditions, i.e. wetter weather. This window puts pressure on time and machinery which ensures the amount of maize grown is limited. The farm is also gradually introducing a higher area of hybrid rye. The case study farmer states that one of the drivers behind this change is to manage soil erosion and the associated problems. Hybrid rye is sown in the winter and harvested in early July. This has positive environmental impacts, but also allows for an early oilseed rape or stubble turnip crop to be established.

The cultivations associated with a wider number of crops has been effective in managing soil compaction. The farm is also incorporating more manures than before, reducing potential nutrient losses. The NFU stated that soil management should improve with the increase in AD investment as AD plants will be driven by crop yields to maximise biogas production. This will encourage better soil management to reduce the risks of crop failure and poor yields. Furthermore, they stated that farmers attitudes to maize are changing and that farmers are more aware of the problems and are being more responsible. However, the NFU does understand that there is an issue with the environmental impacts of maize within the region, but one that cannot be attributed solely to maize for AD.

The EA is aware of the environmental impacts of growing maize in the area, including significant soil erosion events which have resulted in road closures as well as sediment deposits in residential areas, causing large insurance claims. The EA could not fully quantify the impact of AD, but commented that poor crop management with a high risk of soil movement is often observed on land that is growing maize for AD.

The County Council has worked with the Environment Agency to help mitigate problems with maize. They also raised issues of a residential area being flooded in 2012, likely to be the same event the EA mentioned. It is thought this was caused by heavy rain and maize cropping. However, the County

Council did state that "maize exacerbated the flooding in this case, but the local properties may have flooded either way".

The NFU acknowledge the issues that can be caused by maize growth on unsuitable soils, but do not think this is associated with AD plants, while the EA also expressed concerns with a "lack of rotations". They stated that commonly, larger sites can rotate crops to avoid continuous cropping of maize, however there is a concern that smaller farms do not have the land area to increase the number of rotations and as a result use marginal land. Furthermore, the EA has identified that since AD development in the region, maize sites have increased. There are instances where site selection is poor and poses a high risk to soil erosion. High risk fields include sloping and slighter ground. These sites are a major concern, especially when cropped with high risk crops, such as maize. The EA see this as such a large problem within the county that they will be holding a full day event to discuss the management of AD plants and their associated crops.

Water quality

As a result of soil movement, sediment and nutrients such as nitrogen and phosphorous and sediment can enter watercourses. However, both the EA and NFU stated that the advice provided through the Catchment Sensitive Farming (CSF) initiative, EA and the Rivers Trust is having a positive impact on changing farming behaviours and addressing the water quality issues in the region.

The EA also identified problems with digestate storage with experience of tank failures, resulting in point source pollution incidents. However, occurrences of these events are low – "*twice in the last 3 years*" – and there have been no reported incidents regarding the spreading of digestate.

All stakeholders see mitigation as vital. The EA and County Council have worked hard to encourage mitigation in the local area. These include wider buffer strips, better rotations, hedge breaks and improved harvest timings. The EA believes mitigations are effective, however in the past it takes a large negative environmental event for these to be implemented.

Biodiversity

All stakeholders believe this is not dramatically changed by maize although the NFU and EA acknowledge that there will be negative impacts on aquatic habitats associated with sediment and pollutants entering watercourses. The County Council also stated that the impacts were dependent on the farmer and their personal approach to environmental responsibility. The County Council implied that owner-occupier farmers might be more committed to putting in place long term mitigation measures in comparison to rented farms.

The case study farmer believes that habitat for birds and wildlife may be marginally improved due to an increase in winter stubble. The EA comment that if mitigation is in place it can provide habitats for wildlife. The AD plant has facilitated an increase in spring cropping which provides benefits for wildlife. The case study farmers commented on an increased number of lapwings on his farm. This is attributed to the increase on HLS involvement which he reports fits well with the management of the AD plant.

Climate change impacts

The farmer highlighted the environmental benefits of using digestate, therefore reducing the need for the manufacturing of inorganic fertilisers, the Haber process[19], which is fossil fuel intensive. The farm has increased their waste storage capacity by adding a second lagoon to allow for more storage of digestate through the winter. This has also facilitated more appropriate applications.

[19] The Haber process is a chemical reaction that uses nitrogen gas and hydrogen gas to create ammonia

Summary of opportunities and risks

Case study 3 focuses on a medium-sized AD plant in West Midlands which is farmer-owned and run with a mixed feedstock (58 % waste, 42% crop mix). The farmer was motivated to invest in AD to diversify the farm business and believes the installation has given him the opportunity to move towards a more sustainable mixed farming system, with an increase in livestock and an increase in the variety of crops grown.

Risks raised by stakeholders include AD plants securing planning permission with an agricultural waste system and subsequently introducing maize as a feedstock. The case study farmer is flexible in terms of feedstock inputs and has an ambition to reduce the amount of maize feedstock in forthcoming years. Digestate was emphasised as a valuable resource which has been optimised by the farmer by investing in a second lagoon for storage so it can be applied across a range of crops. The EA and County Council recognised the importance of good storage for digestate and identified poor storage as a possible risk but also highlighted a soil erosion and water quality risk that needs to be managed appropriately for sustainable maize cropping.

There were mixed opinions on the impacts of AD on displacement of crops. The NFU and case study farmer do not believe AD is changing the production of crops within the region as a whole as the region has always had very mixed cropping. However the EA consultee believes there is an increase in energy crops, both maize and miscanthus at the expense of other land use. Stakeholders interviewed who commented on land rental prices acknowledged a rise in rents in the last 18 months to 3 years, but which has subsequently stabilised.

9.4 Case Study 4: Mixed agricultural feedstock digester of at least 140 kW in size

Plant location and ownership

This case study relates to a farmer-owned plant based in the south west of England. The AD plant is an 80MW plant with feedstock consisting of dairy slurry, poultry litter and maize. The holding where the AD plant has been developed is rented (three generation AHA tenancy) but the business farms 202 ha of land in total, including 49 ha of owned land and 73 ha of grass rents. The farm is not in an environmental stewardship agreement.

The farm is a mixed enterprise business that is focused around a dairy herd, with arable, sheep and poultry. The farming systems are summarised in

Table 9-6.

The farmer who owns and operates the AD plant was interviewed for this case study and will be referred to as the case study farmer throughout this section. Alongside this other key stakeholders interviewed included the Environment Agency (EA), two locally based Land Agents, referred to as Land Agent 1 and Land Agent 2 and the National Farmers Union (NFU), Area Advisor. The County Council were unable to provide any comments for the project.

Table 9-6 Case Study 4 farm system details

Farm enterprise	Description	Manure management
Dairy	• 170 dairy cows milked 3 times a day by robots. • The cows are housed on cubicles for 365 days of the year with dry cows grazed over the summer months. • All youngstock are reared (bulls and heifers) and housed on straw.	• The slurry from the cubicles is scraped twice a day into a reception pit. This is channelled directly to the feed tank to provide a constant supply of slurry to the digester. • The FYM collected from the youngstock and bulls is spread directly onto the arable land.
Broiler unit	• 30,000 broiler places • There is an 8 week growing cycle. Each shed is empty for a week between batches. There are approximately 5 batches, producing a throughput of 150,000 birds per year	• 18 t of manure is produced per cycle - a total of 450 t pa. • A further 295 tonnes pa is imported from a neighbouring poultry farmer • All of this litter is used as a feedstock (total 745 tonnes pa)
Arable & grassland	• 202 ha of land of which: ○ 41 ha of winter cereals (mainly winter wheat and winter barley) ○ 52 ha of maize (36 ha is grown for the dairy cows and 16 ha is grown as AD feedstock). A single variety is used for both the AD and dairy cows. ○ 81 ha of total grassland (53 ha of cutting ground and 28 ha of grazing ground)	• Digestate produced from the AD plant is separated into liquid and solid digestate. The liquid digestate is applied to the grassland area. No other fertiliser is applied to this ground • The solids from the digester and FYM from the youngstock are applied to the winter stubbles and incorporated for maize and winter cereals.

Reasons for development and plant details

The case study was designated as a Nitrate Vulnerable Zone in 2009. In view of the volumes slurry produced and the requirement to invest in slurry storage, the business looked at investing in AD as a means of waste management. In conjunction with a local consultant the business installed an AD system that their existing farm business could maintain by utilising existing levels of slurry and litter production. The landlord was not interested in a joint venture for the project so the farmer invested in the plant himself, with the understanding that the next two generations will benefit from the investment.

The AD plant was built in 2012 and was fully operational by October 2012. The plant produces 80kW an hour of electricity which is fed into a Combined Heat and Power (CPH) unit. The heat is not currently used. The electricity is used on farm and excess exported to the grid. The electricity provider is Western Power.

During the AD plant development, three milking robots were installed which entail year-round housing of the dairy herd and increased slurry volumes. The plant is operated on a constant supply of slurry from the cubicle buildings plus a further 2 tonnes of maize and 2 tonnes of chicken muck per day.

Land agent 1 commented that a lot of farmers are looking at investing in AD plants to improve and stabilise farm business profit. They also noted that there is an increase in awareness of the nutrient value of digestate. Similarly, land agent 2 stated that farmers are starting to rent land to AD plants to secure an income. This was also stated by the NFU.

Experience of AD plant operation and wider perspectives

<u>AD Activity in the local area</u>

There are three operating AD plants known to the case study farmer in the local area. These are predominately farm based systems and it is understood that they are renting land and importing feedstock to support the plant. There are more plants in the development phase, some of which are expected to be a significant size (>250kW and up to 2MW). One potential developer is actively trying to acquire land for AD maize to secure planning. The case study farmer felt that if there were more large scale plants (larger than 250 kW) then the area would experience a saturation of development which would have consequences on local farming businesses. However, the case study farmer was very supportive of on farm AD that utilises waste and can use the digestate. Land agent 2 is aware of 4 plants within the locality and suggested that the majority of the plants within the county were "self-sufficient" and imported very little feedstock from neighbouring farmers.

The NFU report that there are existing AD plants in the area that have been established for a long time. However, these are mostly food waste plants and not reflective of on farm AD activity. Most of these plants do not import feedstocks such as maize and are having a limited impact on the local farming sector. There are 4-5 new plants progressing through planning (as of March 2015). However, the local Council have had relatively little involvement with AD plant compared to some other counties (unable to confirm this with the county council.). The NFU believes that broadly, in this region the farm scale AD developments are fitting into existing farming systems, not replacing existing ones. For example, maize is being incorporated into cereal rotations. This is reflected by the comments of land agent 2.

<u>Feedstocks and digestate</u>

As indicated previously, the main driver for the case study plant development was the advantage associated with managing slurries and other wastes produced on the farm. Maize was selected as a feedstock firstly because of the high energy value and secondly because of the farmer's familiarity and knowledge of the crop over a long period. The farm uses an independent consultant for advice on maize varieties and a variety that is suitable for both the dairy stock and digester is used. A single variety is grown on the farm.

The farm was growing 36 ha of maize for the dairy stock prior to the installation of the AD plant. Based on the size of the plant, a further 16 ha of maize was grown, increasing the total area of maize from 36 ha to 52 ha. The area of maize grown for the dairy stock has remained unchanged. The additional AD maize was incorporated into the rotation, displacing 16 ha of winter wheat. The farmer rotates the maize (typical rotation: winter cereal, temporary grass ley, maize) as far as possible; however, maize is sometimes grown continuously for 3-5 years. This has always been the case and has not changed due to the addition of the AD plant.

"AD hasn't impacted on what we do at all - it's just using waste products"

Although surplus produce such as potatoes have been offered, the plant does not use imported feedstock due to storage restrictions on the farm.

The analysis of the digestate (taken 2012) is:

- Dry matter: 34%
- Total N: 2.47 kg/t
- P: 13.3 kg/t
- K: 2.7 kg/t
- Mg: 0.6 kg/t

The liquid digestate is used on the grassland (cutting and grazing) which has displaced the requirement for manufacture N, P and K. The solid fraction of the digestate and the farmyard manure is applied to the winter cereals and maize. It is most commonly applied and incorporated into the seedbed. No digestate (liquid or solid) is exported.

The NFU report that farmer members have raised the issues of barriers in managing feedstock for on farm AD. These include the waste management controls enforced by the Environment Agency surrounding permitted wastes. Furthermore, food waste contracts are typically secured by large companies and for up to 20 years. Farmers find it hard to access additional wastes and therefore need to support a plant on their own resources.

<u>Other impacts</u>

Since 2012, the case study farmer has experienced a few complaints from local neighbours. One neighbour complained about the unusual number of flies and approached the plant to suggest the fly population had increased since the development. This was resolved by an on farm visit from the concerned neighbours who were then content the AD plant was not the source. The case study farmer cleans the roads after the maize harvest as standard practice and says he has had no complaints from the County Council.

The NFU report that an issue associated with AD plants locally is the transport associated with moving maize and digestate throughout the county. In the county, the maize growing potential of land varies and it is thought the AD plants in less favourable maize growing areas are importing maize from other areas of the county. It is thought some plants are importing maize from over 50 miles from the plant. In return, the digestate is transported back to this land for spreading. However, it is believed only a few plants are importing from such a distance. The NFU stated that some of the farms interested in AD development do not have the land area to support viable systems and therefore need to import maize.

Displacement of other crops

<u>Case study farm</u>

The case study farm was looking to avoid the volatility of markets by having a range of enterprises on farm. One of the fundamental reasons for this is to encourage succession. Some 16 ha of winter wheat was displaced by maize for the AD plant. The cereal enterprise was only a small fraction of the total farm income and therefore the displacement of the crop had minimal impact on the farming business economics. Cattle numbers have changed since the development of the AD plant. However, the farmer attributes this to the investment in the milking robots which made management of the herd less labour intensive. The farm is looking to increase total cow numbers further to 216 cows.

<u>Regional trends</u>

Land agent 1 specified that locally, maize for AD would mostly be displacing “poorer paying crops” such as grass, spring barley, spring oats and oilseed rape. Land agent 2 understood that the majority of farmers now renting out land for AD feedstock were previously renting land out to local dairy farmers. Therefore, there has been a minimal impact of cropping patterns. The change is associated with the end use of the crop. Both land agents stated that the farmers renting out land for AD feedstock are looking to secure an income. The volatility in cereal markets and the increasing number of dairy farmers that are leaving the industry is a concern for farmers renting out land. The EA understood that maize would be displacing grass crops because of the economics of growing maize for AD. Similarly, the EA also suggested that extensive beef and sheep systems may consider growing maize, driven by economics. However, this view was not shared by the other stakeholders.

The NFU report that anecdotal evidence suggests that dairy farmers close to retirement or without a succession plan are renting out their farmland to grow maize for AD. Furthermore, dairy farmers struggling to withstand the volatility in milk price may be pushed to look at alternative revenue streams. Producing maize and other feedstock for AD is mostly a lifestyle or business choice not necessarily associated with substantial financial pressures. These changes cannot be exclusively attributed to AD in the county.

Land agent 2 provided an example of a typical rotation for land that is rented for maize feedstock. The cropping consisted of maize, wholecrop wheat, energy beet and grass silage/whole crop rye. Some arable farmers locally are using maize grown for AD as a break crop. However, the arable area is relatively small locally and weed stress, such as blackgrass, are not a major concern. The land agents interviewed commented that, while each case is different, cropping of maize is dependent on "what is trying to be achieved". For example, some are incorporating maize as a break crop or to satisfy the Ecological Focus Area (EFA) requirement of the new Basic Payment Scheme (BPS). This is also dependent on the predominant farm type in the area.

The Environment Agency report that the area of maize in the south west has always been high. In the 1980s maize growth was exponential, but has plateaued in the last 10 years. This increase was attributed to growing use in the dairy sector. It is expected that maize production will experience another increase following the increase in AD development, but this is unsubstantiated. The trend in maize production for AD is being led by a change in cultural behaviour, driven through subsidies for AD. The main drivers are commercial pressures, for example the need for break crops as weed controls and an increasingly commercial trading environment. Other stakeholders have suggested that the maize area has not be influenced by AD development and has remained constant.

Economic impacts

Land rental impacts

The farm business is mostly comprised of rented land (farm tenancy and casual agreements) but does not rent additional land to grow feedstock for the AD plant. Anecdotally the case study farmer has said that there has been an increase in land rents locally, referencing a £300/ac rental price for maize ground, however he did not have "first-hand knowledge of this change". "*Going back a few years, rent was £140/ac and £100/ac for grass lets*" (this is in reference to a local dairy farm that has recently been rented). Similarly, the land agents interviewed suggested that in some areas the land rental price had increased by up to 50%, from £60-£80 to £100-£120 per acre for dairy land around commissioned AD plants. Land agent 2 had experience of drawing up rental agreements for AD feedstock at £150 per acre. Both land agents noted an increase in land rental within the first 12 months of the AD plant being commissioned. Both of the land agents confirmed that land rental (price and availability) was effected within the locality of operating AD sites. For example, the land rental value across the whole of the county will not be affected. However, land within a 10 – 20 mile radius of an operating plant will be impacted. Furthermore, the case study farmer also commented that a local vegetable grower has also had to increase his rent payment to compete with ground rented for maize "*because they can offer* *twice as much*". This cannot be fully attributed to maize ground for AD feedstock, but anecdotally land is becoming less available locally and more expensive as the "*hunger for maize ground increases*". Other competition includes land for dairying.

Similarly, land agent 2 commented that AD activity locally will have detrimental impacts on dairy farmers. A number of large dairy businesses have built up their farm area through land rental. This is mostly for maize and other forage crops such as wholecrop wheat. They are now being outcompeted by AD companies who are able to offer a higher rent.

The NFU comments that there have been no changes in land rental value in the area to date that can be attributed to maize ground for AD. However, "*this is the number one worry for members who are not involved in AD. They have seen the implications in Shropshire and Cheshire*". The main concern surrounding the land rental is availability. These concerns are raised by farmers who have built up businesses based on renting land, or smaller businesses, specifically dairy, which rent ground for forage crops. This was confirmed by the other stakeholders interviewed.

The land agents interviewed for this case study commented that the rental agreements for renting land in and/or out for AD feedstock vary widely according to the individual circumstances. Farmers who are required to demonstrate that they are actively farming for tax relief and Basic Payment Scheme (BPS) purposes require different agreements to land owners who are renting out land. Agreements can include contract farming agreements and guaranteed income or fixed rates for 3-5 year periods (short term agreements). Land agent 1 suggested that very few rental agreements for growing AD feedstock will be on long term tenancies. However, land agent 2 had first-hand knowledge of an AD company that was trying to secure a rental agreement for the 20 year life of the plant. Both of the land agents estimated that a very small proportion (*c*. 5%) of rented land in the locality is rented for feedstock.

There has been a noted increase in the number of farmers renting land. Land agent 2 suggested there is an increasing trend in farmers renting out land that they have not rented previously, which can be attributed to AD and the security of the feedstock market. Land agent 2 suggested that a high proportion of AD companies are dealing with farmers directly and pulling together relatively informally and potentially "risky" rental agreements for the land owner. In the locality, they feel there are minimal land agents and other professionals involved in land rental agreements between the farmers/land owners and AD operators.

Overall, there has been an increase in the land rental value in the area. Land agent 1 suggested an increased pressure to cultivate marginal land. However, land agent 2 stated that the rental value of AD feedstock is typically a flat rate with possible deductions if the agreed yield is not met. Therefore, farmers avoid cultivating marginal land to minimise the risk of crop failure and poorer yields.

The estimated changes to land rental agreements over the past 5 years, as provided by the land agents interviewed for this case study are:

- Full Agricultural Tenancy (FAT): + 20%
- Farm Business Tenancy (FBT): + 35%
- Seasonal rental agreements: + 20%

Furthermore, land agent 1 stated that of this increase, AD pressure can be attributed to approximately 20% of the change. However, land rental prices and availability are typically only influenced with the close proximity to an AD plant. Other influencing factors include dairy farm competition. Land agent 2 stated that, up to 18 months ago the dairy sector was very strong and the competition for maize ground had increased. Land rental competition between dairy farmers has since declined in response to the sharp decline in milk price. The land agent suggested that maize for AD was "*filling this rental opportunity*".

In some instances farmers are putting in joint agreements for longer FBTs and averaging the costs out between numerous crops. Land agent 1 commented that land rental agreements for maize as a feedstock can be likened to other high value crops such as potatoes and vegetables and the changes in market prices – for example higher cereals prices is impacts on land rental.

<u>Economics of the plant</u>

The economic opportunity for an AD plant was identified as a slurry management approach to coincide the requirement for slurry storage under the NVZ rules. The economics for the AD plant are predominately based on the income from electricity generation (including subsidies) for sales and the savings in farm energy use and fertilisers. One of the main benefits of the AD plant is this production of digestate which has a higher nutrient value than the dairy slurries and manures previously produced. The digestate produced has replaced all of the inorganic fertiliser that was previously applied to the total grassland area (81 ha) which has resulted in a significant financial saving. Based on Feb 2015 fertiliser prices, the digestate is worth approximately to £12/t. Fertiliser use on the maize and winter cereals has remained unchanged.

Table 9-7 below outlines the income generated from the AD plant, the money saved via renewable energy generation and the costs associated with the plant.

The costing takes into consideration the maintenance and breakdown costs of the plant. The general maintenance of the plant is expected to be considerably less that £15,000 pa. However, due to the breakdown costs of the plant, an average of £15,000 pa is estimated. For example, for this plant the motor is running for 24 hours a day, at full speed and therefore breakdowns are frequent. The case study farmer predicts that the breakdown costs are £5,000 - £6,000 more per annum that expected in the plans of the project.

In addition to the breakdown costs, there is also an implication on loss of income generated when the plant is not generating electricity. Insurance was also an underestimated cost. Examples of costs include:

- Replacement of the motor every 3 years (£10,000 per motor)
- Servicing of the machine every 3 years.
- Maintenance of the separator which breaks down more often than predicted.

One of the main benefits of the AD plant is this production of digestate which has a higher nutrient value than the dairy slurries and manures previously produced. The digestate produced has replaced all of the inorganic fertiliser that was previously applied to the total grassland area (81 ha) which has resulted in a significant financial saving. Based on Feb 2015 fertiliser prices, the digestate is worth approximately to £12/t. Fertiliser use on the maize and winter cereals has remained unchanged.

It is estimated that the net costs of growing and harvesting maize offset the net income from growing cereals. Due to the relatively small displacement impact of winter wheat the economics of cereal vs. maize production has remained unchanged. Fertiliser and contractor use and cultivation techniques have remained consistent. The farm uses an agronomist for nutrient planning and pesticide management for both maize and wheat. The farm also employs a contractor for establishment and harvest of both crops. The alterations in crop area did not affect this.

Table 9-7 Returns and costs for Case Study 4 AD plant

		Annual income (£)	Annual cost (£)
Feed In Tariff		£88,000	
Exported electricity		£18,000	
Additional Income		**£106,000**	
Electricity	Everything on the farm, including the farmhouse is run on the electricity produced by the plant.	£12,000	
Fertiliser	Manufactured fertiliser is no longer applied to the grazing or cutting grassland (81ha)	£16.000	
Costs savings		**£28,000**	
Displaced crop	Net margin from growing and harvesting 16 ha of cereals (est. at £500/ha)		£8,000
Poultry litter sales	295 tonnes of poultry litter imported per annum @ £7/tonne		£2,000
Income forgone			**£10,000**
Repayment of loan on initial investment	AD plant technology and associated digestate and feedstock storage (i.e. additional maize clamps). Total loan of £600,000 repaid (capital and interest) over at 4% interest over 10 years.		£60,000
Insurance			£4,500
Labour for plant operation	No additional labour (2 hours per day)		£0
Plant parts and servicing costs etc	This includes general maintenance and breakdowns		£15,000
Costs for extra maize	Total costs associated with growing and harvesting 16 ha of maize (est. at £500/ha)		£8,000
Cost of spreading digestate	Increase in contractors costs of approximately 20%		£5,000
Additional costs			**£92,500**
Totals		**£134,000**	**£102,500**
Net income		**£31,500**	

The case study farmer states that the contractor invoice for crop work has remained unchanged, however there has been an increase of *c.*20% for the spreading of digestate. Sub-soiling/compaction alleviation methods were already employed previously to growing additional maize. The labour requirements on farm have remained the same. There are additional benefits to growing more maize, such as weed control. However, in the area weed pressures are less of an issue and therefore this is a marginal benefit which is not impacting on yield.

In summary the farmer considers the AD plant to have a very positive impact on the existing business. The turnover of the business has increased significantly by >£100,000. However, fixed and variable costs have also increased. The case study farmer estimates that his total income is now £130,000 per year higher and the AD plant has increased profit by >£30,000 per year. The payback period for the plant is estimated at 10 years. The farm is now looking to utilise the heat produced and therefore RHI to generate an additional revenue stream. The aim is to heat the farm office and poultry houses.

<u>Wider economic impacts</u>
The case study farmer reported that there has also been positive economic impacts on local business. The local contractor has seen an increase in business, firstly in the crop establishment and harvesting of maize, secondly through the application of digestate, are thirdly, the servicing of the AD plant. The contractor used by the case study farmer is a qualified engineer and so has been able to transfer his skills to servicing the AD plant. Land agent 1 interviewed also commented that many farmers do not have the machinery to cultivate and harvest maize crops and as a result are using more contractors. This is also the case for digestate spreading. Land agent 1 questioned whether the demand for maize contractors will exceed the current supply, therefore suggesting this could be a potential industry for economic growth. However, land agent 2 stated that the majority of AD companies, especially on funded sites, use their own contractors for maize cultivations and harvest. Therefore, within the locality of these plants, there is a risk that smaller, independent contractors will be disadvantaged.

Furthermore, the poultry business local to the case study farm is now able to sell the poultry litter produced on farm to neighbouring AD plants. The farmer is in a designated NVZ and therefore under pressure to export manure for compliance. Prior to AD activity in the area, the farmer was exporting muck to arable famers for £2/tonne as a fertiliser but the business is now able to sell the manure as an AD feedstock for £7/tonne.

The plant received no community investment, but does provide tours and allows the plant to be used as an educational facility.

Environmental impacts
A summary of comments from the case study farmer and wider stakeholders is given below.

<u>Soil erosion, quality and structure</u>
The case study had previously been growing a relatively large proportion of maize and was managing compaction issues appropriately to mitigate soil loss and to increase yields. However, more widely there are contrasting views on the scale of environmental risks from expansion of maize for AD.

The NFU report that it is likely there will be no soil erosion changes associated with AD maize. The NFU state that the area has always been a "*maize growing county*" and that the inclusion of AD maize will have little impact because the overall area of maize will remain relatively unchanged due to changes in the dairy industry. However, both the EA and land agent 1 stated that there would be an increase in soil erosion and therefore the levels of nutrient and sediment in rivers associated with increased maize production for feedstock. The EA expressed concerns that there would be an increase in cultivation of marginal land to accommodate AD maize and displaced crops, which would have an increased pollution risk potential.

The EA report that areas of the south west have a high pollution risk due to soil type, slope and annual rainfall which are unsuitable for maize cultivations. Further, while a typical rotation in the area would not uncommonly include 3-5 years of continuous maize but some sites have had continuous maize for over 20 years. The issues surrounding maize production and associated soil loss and water quality issues in the region are already apparent and while the impact of AD development on the issues is unclear, it is expected to add to risks. However, the NFU state that there is an acknowledgement of the soil and erosion concerns surrounding maize within the farming industry, noting "the majority of farmers growing maize are aware of these". While the EA also acknowledge that farmers are “relatively clued-in generally to compaction”, they comment that buffer strips and other mitigation measures are usually only implemented as part of a wider scheme such as ELS and potentially under EFA’s going forward. More general actions to alleviate compaction and other measures such as cover crops are not widely implemented.

All of the stakeholders interviewed did not consider the current cross compliance measures, nor the new measures under the Basic Payment Scheme to be a decision making factor for farmers/growers when planning maize sites, cultivations and harvest.

Water quality

Any loss of soil has potential impacts for water quality locally, specifically soil turbidity and the associated nutrients that enter watercourses. In addition to this and the comments above, incidents have been reported to the EA regarding digestate storage and management. Mostly these have been a result of inadequate storage and store failures. There is a concern within the EA that a large proportion of farmers investing in AD plants and associated infrastructure – slurry and maize stores – are unfamiliar with the Silage, Slurry and Agricultural Fuel Oil (SSAFO) Regulations and therefore are constructing stores to a lower standard and are at risk of polluting. Further, the EA state that although farmers using digestate are typically using a nutrient management plan, spreading can occur at inappropriate times of the year and samples (digestate and soils) are not always taken regularly.

Biodiversity

The case study farmer and NFU advisor were unable to comment on this topic. However, one of the land agents generalised that maize stubbles aren’t “as valuable as cereal crops in winter” which may impact bird populations.

Climate change impacts

Part of the planning application case was that carbon emissions from the farm are less after the building of a plant. In this case study, neither maize nor digestate is transported to other farm so any impacts relate to changes in fertiliser use or livestock numbers. There is also a saving in the electricity usage (on-farm and exported electricity) that has been displaced by renewable energy generation.

Summary of opportunities and risks

This farm is a good example of farm scale AD that is utilising the farm manures and incorporating land management changes into the existing system with limited change. The farmer believes that the addition of the AD plant to his farm has been positive and had a very low impact on the local area. In terms of economics it has made the farm more robust commercially and will secure it for successors.

Given the limited enterprise changes, the farmer believes the environmental impacts on soil and water have been minimal while there are gains in terms of reduced fertiliser use and displacement of fossil-fuel energy. There are future opportunities on the farm to harvest the heat produced from the plant. No additional land is rented so there is no direct impact on land rental prices locally. However, all of the stakeholders interviewed share concerns about rising land rental pressures, particularly as much of the land in the area of marginal land for maize growth. It was indicated that the main concerns are around larger plants where maize is the predominant feedstock rather than waste products or farm manures. Although these are concerns for the future, currently none of the interviewees committed to attributing any land rental changes to AD in the local area.

9.5 Views of farmers outside the AD feedstock supply chain.

While the case studies of AD plants included views on land rental impacts from AD plants and farmers supplying maize as a feedstock, it is important to get wider views from those outside the AD supply chain, particularly those that might be directly impacted through competition for rented land. It was planned that this would be in the form of two workshops, one in the east and one in the west of the country using ADAS contacts and other farming connections. Unfortunately not enough farmers were able to attend to make the focus groups feasible. Reasons included not being interested and being too busy due to the time of the year (early spring). Therefore a call for people affected by AD, both positively and negatively, was made using email networks and social media. Approximately fifteen tweets were sent from four twitter accounts with a link to a news article on the ADAS website[20], the tweets also included handles and hashtags that were associated with the farming community for example @farmingforums and #agrichatuk.

Farmers who contacted the research group received a questionnaire which was completed via email or telephone interview. Data was collected form eleven farmers nationally. Ten were negative and one positive. The positive response was from a farmer who grew maize for AD so is not included in this report. While our main interest is land rental impacts, comments were also captured on environmental and other impacts. The responses are summarised on the basis of geography to reflect the distinct systems (both in terms of AD scale and feedstock mix, and enterprises displaced).

East of England

Three responses were received from the East Anglia region and are summarised below. One farmer completed the questionnaire while the other two gave limited views by telephone, mainly due to time constraints. The farms included a small research farm and two arable farms (90 hectares and 202 hectares). All of the farms rented some land in the local area.

Land rental prices

All farmers reported an increase in land rental prices. One farmer was unable to quantify the increase but the others independently quoted an approximate increase of twenty percent on land rental agreements. One farmer, who mainly has FBTs, commented that he had to negotiate very hard to retain the same land for rental.

Although all farmers stated that land rentals did increase there was no effect on the amount of land farmed, as alternative agreements were found. One farmer moved 30 hectares grown for oilseed rape to alternative land due to competition for the FBT land from maize for an AD plant approximately 20 miles from the farm. They expressed concerns about long term farming and reaping the benefits from doing the correct land management processes in future years.

“”AD plants are reputedly paying up to £400/acre without the BPS payment”

All three farmers associated rises in land rental prices with AD plants in the local area, but were also aware of other drivers such as expansion of potato growing and solar farms.

Environmental impacts

Only the farmer who went through the questionnaire made comments on environmental impacts. Concerns over soil damage and erosion were raised. The farmer stated he witnessed nearby farms harvesting maize for long periods and at the wrong time in the season. This led to soil on the road which has caused friction between the community and farmers in the local area.

[20] http://www.adas.uk/News/is-ad-impacting-your-business

"The chopper was used 24 hours a day, often not on suitable land. After maize growing the soil is a disgrace"

Other impacts

Two out of three of the farmers raised concerns over growing bioenergy crops instead of food and the impacts this has had on farmers growing food. Haulage was raised as an issue. One farmer believed maize was being hauled up to 20 miles away. He reported poor practice had taken place as the farmers in the area are not knowledgeable on growing and harvesting maize, leading to issues which have had a very negative impact on relations with the local community. One farmer did acknowledge that there is a lot variation between AD plants and management of them is very different.

"Although commercially attractive it is not sustainable as an energy source without subsidy, it is inflating land rents, thereby prohibiting some new entrants into farming and putting other crop growing costs up."

South West

Three farmers in the South-West responded and all three agreed to go through the questionnaire. All were dairy farmers and included a small self-owned farm, and two larger units (125 and 113 hectares) that rented the majority of their land on short term contracts.

Land rental prices

The larger farms had several different short term rental agreements, including FBTs and informal agreements, and one also used grazing agreements. The dairy farmer with 125 hectares, rented 40 hectares in total and quoted rents from 5 years previously ranging from £20-£60/ ha in comparison to current rents at around £120/ ha. The other dairy farmer stated that his rent has increased from around £60/ ha to £80/ha but rents of £90/ha have also been asked for. Both farmers who commented on land rental prices attribute the rise in AD as the main driver of rent in the area.

Although their land rental prices have been increasing, neither of the farmers have changed their current practices. One farmer stated he has not expanded due to the increase in land rental and another commented that the additional squeeze from a decrease in milk prices more recently may push him to change practices.

"I fail to comprehend the thinking that allows government interference to take land out of food production to allow short term financial gain for some farmers, whilst increasing the cost of forage for others"

"I think they (AD plants) are the main driver (of land rental) in my area"

Environmental impacts

Of the three farmers who responded, again only one gave their opinion on the environmental impacts. This farmer believes that damage to the soil from growing maize is greater and there is no evidence of cover crops being used in the local area. He claims to have witnessed run off into his grass field. It was acknowledged that mitigation could help these impacts and a lot of the negative environmental impacts were due to naivety from the AD maize growers and plant owners. The same farmer does however appreciate the positive impact that AD digestate can have on soils.

"Fortunately some landowners will not let to AD plants because maize can be very destructive to the soil"

Other impacts

Two of the farmers objected to AD on the grounds of taking land out of production for food to provide energy. The other raised issues of increased traffic and haulage in the area, often using unsuitable vehicles and inexperienced labour.

"Considerable road traffic form long distance hauls (20 miles) by tractor and trailer of maize crops during harvest. Also locally the road to our farm was left covered in mud and flints. "

West Midlands

Only one response was received from the West Midlands. This is surprising due to the amount of AD plants in the area. In such an AD intensive community it is likely that people have both business and personal connections to farmers with AD plants. The farm that responded runs a large 400 hectare mixed farm. There are 4 AD plants within ten miles of the farm.

Land rental prices

The farm is half owned and half rented on FBT contracts. The farmer said land rental prices had increased from £120- £130 per hectare before the increase in AD plants to current prices in excess of £200 (with no single farm payment). They also raised concerns that the farmers growing maize for AD were receiving double subsidy; the first under SPS and the second from the subsidies for the electricity produced.

"The question that most non-AD farmers have is why the ground growing maize for the AD plants should be eligible for SFP and again receive subsidy when that maize is used in the AD plant to produce electric, effectively receiving double subsidy."

This farmer has maintained the amount of land farmed but has had to pay an increased price. He believes a lot of smaller dairy farmers are being priced out of the rental market.

Environmental impacts

No environmental impacts were mentioned.

Other impacts

Other economic impacts were raised, namely that the price of manure and fodder are also increasing as they are being used to feed AD plants. This includes fodder beet and broiler manure, again increasing pressure on other farmers in the local area.

"So in brief they have affected local arable dairy beef and sheep farms. Only my point of view but one held by many locally."

Other areas in the UK

Three other responses were received, two from South East and one from the North of England. All of the farms had FBT rentals and one owned land. The two farmers in the South East were arable farmers with farm sizes of 400 hectares and 1800 hectares. The farm in the North of England was a mixed traditional system of beef, sheep and arable.

Land rental price

The two farmers from the south-east commented that there was an increase in rental prices due to AD. This was quoted at 15% from one farmer and approximately 20-30% from the other. Both state that general competition in farming caused land rental price increases in the local area, but believe that the growth of maize for feedstock is a large influence. The third farmer in the North of England believes they have not been able to renew their FBTs, which they have had continuously for at last 14 years, as the landowner intends to grow maize for AD (this is a land use competition rather than a land rental price effect).

"The local farmers cannot compete for land to service traditional beef, sheep and arable sectors"

"Open market tenders until last year had gone from around £170/acre to £220-250/acre for arable land. The first open market tender for arable land this year was completed last week. Rent reviews had been fixing £150 to £170 but due to location of open market offer some 8 miles from (local) AD plant it seems bids in excess of £200/acre has been tendered"

"AD maize feedstock is skewing the rental market and permanently increasing the cost base of food production from rented land. We could alter the subsidy for energy produced from AD, limit the number in an area, and limit the size by insisting that any farm operator can only use feedstock from his own holding."

Environmental impacts

One farmer in the South East believes soil erosion has increased and water quality has decreased due to the increase in maize growth. The other farmer speculates that he expects it could be worse. A farmer in the South East recognised how useful digestate can be; however he raised the concern about the size of the AD plant and the ability to store and use the digestate responsibly.

Other impacts

One South East farmer believes the amount of mycotoxins in his milling wheat has increased since there has been an increase of maize growing on neighbouring farms, possibly due to an increase in run off and spreading of soil-borne mycotoxins.

Summary

This limited consultation reflects responses from those who have negative experiences and/or opinions of maize for AD who have been motivated to comment. These comments do not necessarily represent the experiences of the wider population of farmers, operating in proximity to AD plants. As such the evidence is relevant but not reliable and should be considered alongside the more positive responses from those within the AD feedstock supply chain in the four case studies. Together they provide insight rather than reliable evidence of impact.

In summary, the majority of farmers in this very small sample report an increase in land rental prices on short term land rental contracts, especially 3-5 year FBTs. Some farmers have a fundamental issue with the policy approach of supporting crops for energy which displace food. A key theme from all regions is the steep learning curve for those growing maize for AD, both in terms of land rentals being paid and environmental mitigation.

Table 9-8: External views on maize AD

Region	No. of respondents	Estimated land rental impacts	Environmental impacts	Other impacts
East of England	3	+20%	Increased soil damage and erosion	Increased traffic and haulage
South West	3	+25%	Increased soil damage; positive impact of digestate on soils	Increased traffic and haulage
West Midlands	1	+50%	N/A	Increased price of poultry manure and fodder
Other areas	3	+15-30%	Increased soil erosion; water pollution from digestate	Mycotoxins?