



Scottish Environment Protection Agency

Investigation into plastic
in food waste derived
digestate and soil

Project report

Written by

Aspray TJ (Heriot-Watt University)

Dimambro ME and Steiner HJ (Cambridge Eco Ltd)

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Cover images: Top – plastic fragments from a digestate sample ready for surface area scanning.
Bottom – past example of visible plastic fragments on a grassland field site (actual field not part of this work)

Executive summary

A key aspect of a circular economy in Scotland is the separate collection and treatment of food waste through anaerobic digestion to produce a fertiliser suitable for use in agriculture and biogas to generate energy. This has led to increased investment in the sector and a significant increase in the amount of digestate being produced. In order to ensure that soil quality is protected and improved through the use of food waste derived digestate, more information is needed regarding the environmental effect of potential plastic contained in waste derived digestate on the soil environment and crop health/growth.

The Scottish Environment Protection Agency (SEPA) proposes to align physical contaminant limits for PAS110 digestate in Scotland with Quality Meat Scotland (QMS) and Scottish Quality Crops (SQC) standards. The limits will be adjusted in increments with 50 % of PAS110 limit in April 2017 followed by 25% and 8 % in April 2018 and 2019 respectively. The objectives of this project were:

1. Understand previous work on plastic in digestates and soils
2. Through laboratory analysis, develop a knowledge base of the types, quantity and particle size of plastic that may be found in food waste derived digestate
3. Through field work and laboratory analysis, develop a knowledge base of the behaviour and distribution of plastic in agricultural soils that have had digestate applied in the past and assess the likely impact on soil function.

Results

1. Literature review: The presence of physical contaminants in digestate was found to be dependent on two main factors;
 - their abundance in the original feedstock and
 - the extent of on-site separation.

All commonly recognised plastic types are associated with food packaging and therefore could potentially be found in digestate produced from food waste. There are currently two main approaches used globally to measure the abundance of plastics in digestate.

- In the UK, for PAS110 certified digestates, physical contaminants (as a group including plastics) are assessed using a weight based approach. The German Institute for Quality Assurance and Certification (RAL) deemed the weight fraction limit of 0.5% DM for physical contaminants to be insufficient, due to low density, high surface area film plastics having the potential to dominate the visual appearance once the compost or digestate is applied to the field.
- Hence, in addition to the physical contaminant weight limit, optically measuring and reporting the surface area parameter was introduced in 2006, applied only to those composts or digestates that contained >0.1% DM physical contaminants.

Regarding the effect of plastics on soils and crops, it was found that in the UK there is a range of guidance available on the use of digestates in agriculture; however, no published research on the abundance or distribution of plastic contamination within soils currently exists. In fact, no published industry method exists currently for the analysis of physical contaminants (and plastic specifically) in soils. Limited literature on the risk of plastic polymers on soil quality and crop function was found.

2. Lab analysis of plastic in digestate: 15 discrete digestate samples were collected from three UK based PAS110 certified sites. Samples were processed with a modified PAS110 physical contaminant test method to obtain all plastic fragments $\geq 2\text{mm}$ in size. Subsequently weight, surface area, 'particle size' (bounding rectangle length and width) and polymer type analysis were determined. Weight, surface area and size data for plastic contamination from a fourth PAS110 site was also made available for this project.

The weight based analysis showed that three of the four sites assessed were producing digestate of suitable quality (in plastic contamination terms) to meet SEPA's 2017 and 2018 limits through high selectivity of feedstocks and post digestion screening. However, the more stringent 2019 limit could cause periodic failures with current feedstock selection and screening practices.

Fourier transform infrared spectroscopy was used to classify polymer types of digestate recovered fragments, and showed all common plastic polymer types could be found including evidence of several biodegradable polymers types. The relative make up of polymers varied from site to site and, although untested, is expected to vary with time at single sites with changing feedstock supplies.

3. Field work and laboratory analysis, of agricultural soils that have had digestate applied in the past: samples were collected from four fields on one farm representing arable and grassland with and without history of multiple PAS110 certified digestate application. Five locations with depths 0-5, 5-15 and 15-25 cm were sampled per field. An original wet sieving approach was trialled and validated in this project. Using this approach plastic fragments $\geq 2\text{ mm}$ were recovered from the grassland field with digestate application at surface (0-5 cm) depth only. No plastic fragments $>2\text{ mm}$ were recovered from the arable field with digestate application.

Recommendations

- Food waste producers, collection service providers, local councils and householders to continue to improve AD feedstock quality.
- Food waste collectors and AD operators should better assess potential feedstock quality in order to invest in appropriate depackaging and post-digestion screening equipment.
- The industry should agree a protocol for weight based digestate physical contaminant analysis which includes reporting limit requirements.
- Stakeholder engagement is needed to determine whether the AD industry would be supportive of the addition of a surface area measure or separate film plastic weight limit to help provide greater assurance of digestate quality.
- Development of bespoke reference library to include an increased number of relevant bioplastic polymer reference materials (work ongoing)
- Analysis of PVC fragments for phthalate additives.
- Use a higher frequency of soil sampling to give a more robust measure of plastic distribution and abundance at the field scale.
- Develop methods for isolation of fragments $<2\text{ mm}$ from soil (particularly those subjected to cultivation).
- Further studies are to be undertaken to be able to fully assess the risks of plastics on soil quality/function and crop health/growth.

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Glossary

AD	Anaerobic digestion
ATR	Attenuated total reflectance
BCS	Biofertiliser Certification Scheme
BGK	German Compost Quality Assurance Organisation (Bundesgütegemeinschaft Kompost)
BSI	British Standards Institute
CFW	Commercial food waste
DM	Dry matter
dp	decimal place
DW	Dry weight
EA	Environment Agency
FT-IR	Fourier transform infrared spectroscopy
FM	Fresh matter
HDPE	High density polyethylene
HWU	Heriot-Watt University
LDPE	Low density polyethylene
MBT	Mechanical biological treatment
MC	Moisture content
MRF	Material Recovery Facility
NIR	Near-infrared
NVZ	Nitrate Vulnerable Zone
OM	Organic matter
ORG	Organics Recycling Group
PAM	Polyacrylamide
PAS	Publicly Available Specification
PBAT	Polybutyrate
PBS	Polybutylene succinate
PCBs	Polychlorinated biphenyls
PE	Polyethylene
PET	Polyethylene terephthalate
PHB	Polyhydroxybutyrate
PLA	Polylactic acid
POPs	Persistent organic pollutants
PP	Polypropylene
PS	Polystyrene
PSD	Particle size distribution
PTEs	Potentially toxic elements (i.e. cadmium, chromium, copper, mercury, nickel, lead, zinc)
PVC	Polyvinyl chloride
QMS	Quality Meat Scotland

RAL	The German Institute for Quality Assurance and Certification
RAN	Readily Available Nitrogen
REA	Renewable Energy Association
REAL	Renewable Energy Assurance Limited
SQC	Scottish Quality Crops
SEPA	Scottish Environment Protection Agency
SOP	Standard operating procedure
TPS	Thermoplastic starch
WRAP	Waste & Resources Action Programme

1.0 Introduction

The UK is amongst the most advanced countries in the world when it comes to physical contaminant limits for composts and digestates. In Scotland especially, farm assurance scheme Quality Meat Scotland (QMS), and more recently Scottish Quality Crops (SQC), are being influential in driving lower physical contaminant limits. Now the Scottish Environment Protection Agency (SEPA) proposes to align end of waste criteria in Scotland with QMS and SQC standards. Such measures will be important in protecting market assurance in Scotland and may be considered by the rest of the UK and further afield.

Scotland has ambitious targets when it comes to waste and resources. For example, the Waste (Scotland) Regulations 2012, which came into effect in 2014, requires food businesses to separate food waste for recycling and local authorities to provide a household collection service unless the rural exemption applies. This has led to a significant increase in the tonnage of waste processed by 'merchant-fed' anaerobic digestion (AD) sites in Scotland (Zero Waste Scotland, 2016). In 2014, just short of 200,000 tonnes of digestate was produced at Scottish merchant-fed AD sites (i.e. those taking waste from multiple sources such as local authorities and hospitality sectors), with agriculture being the main outlet for the digestate.

Based on 2 million tonnes of food waste produced every year in Scotland, and assuming a 70% capture rate (source segregated), approximately 1.1 million tonnes of digestate could be produced from food waste AD (Zero Waste Scotland, 2010). Agriculture is clearly an important outlet for food waste derived digestate. However, contamination entering AD systems, particularly from local authority and supermarket/hospitality sectors, can make its way into digestates (WRAP, 2011a) and thereby potentially be applied to land.

A recent review by SEPA highlighted that there are a number of areas where our understanding of PAS110 digestate application needs to be improved, including possible impacts on soil quality and an assessment of a wider range of potential contaminants (Cundill et al., 2012).

Project aim

The overall aim of this project was to begin to investigate the potential impact of plastic contamination in agricultural soils to inform decision making regarding the production and use of food waste derived fertilisers. This project will focus on the application of PAS110 certified food waste derived digestate to agricultural land.

The three project objectives were:

1. Understand previous work in the areas of the amounts of plastic in digestates and soils
2. Through laboratory analysis, develop a knowledge base of the types, quantity and particle size of plastic commonly found in food waste derived digestate
3. Through field work and laboratory analysis, develop a knowledge base of the behaviour and distribution of plastic in agricultural soils that have had digestate applied in the past and assess the likely impact on soil function.

2.0 Objective 1. Review of previous work on plastics in food waste, digestates and soil environment

The main research areas of the literature review were:

1. Food waste digestate application in agriculture
2. The types and quantities of plastics within food waste based digestates
3. The effect of plastics on soil quality/function and crop health/growth

2.1 Literature review method

Peer review literature was searched using the Web of Science™ database. The titles and abstracts retrieved from these searches were screened, and relevant articles obtained via Heriot-Watt University (HWU) publishing house and journal subscriptions, interlibrary loans and/or by directly contacting lead authors. In addition to the standardised interrogations of the academic databases mentioned above, unstructured searches were carried out using publically available internet search engines (e.g. Google, Google Scholar, Yahoo, Google.de). For grey literature searches using internet search engines there are always an almost infinite number of hits, and so only relevant web pages were investigated. SEPA, Waste & Resources Action Programme (WRAP), Environment Agency (EA) and Organics Recycling Group (ORG) websites and sources were also interrogated, as well as the project team's databases and libraries.

A wide range of key words and search terms were used to maximise the number of relevant articles found. For example for 'digestate' search terms used included digestate, anaerobic digestion residue, anaerobically digested, anaerobic fermentation residue, fermented residue, biogas residue, biogas slurry, biogas effluent plus a combination of other keywords such 'whole', 'liquor', 'liquid', 'separated', 'fibre', 'fiber' and 'solid'. For physical contaminants, a number of key words are used globally including 'impurities', 'inerts' and 'foreign matter' (Aspray, 2016), in addition to 'plastic'.

The literature review focussed firstly on publications in Scotland, then the UK, and where insufficient data was found, the search was extended to the rest of the world. In addition to literature published in English, articles written in German were also investigated, since AD is well-established in German speaking countries, with the above search terms employed in German language equivalents.

2.2 Literature review results: Food waste digestate application in agriculture

There are three types of digestate (whole, liquid and fibre), with whole digestate being the most commonly available in Scotland (Zero Waste Scotland, 2016). The fibre fraction typically has a dry matter (DM) content of 20-40%, and the whole/liquid fraction 1-6%, although these proportions will vary depending upon input materials, as well as, the separation process or processes employed (WRAP, 2011b). In Scotland, where digestate has met the standards set out in PAS 110 (BSI, 2014) and complies with the SEPA regulatory position statement (SEPA, 2014) [*SEPA document withdrawn and superseded during the course of this project*] it is considered as fully recovered and therefore is no longer regarded as a waste material.

There are a range of guidance documents available to farmers which summarise the main benefits of digestates, fertiliser value and how to apply (WRAP, 2012b, ZWS and NFUS, 2015).

2.2.1 How much digestate to apply

In UK agriculture, optimising the quantity of nitrogen (N) to apply in agriculture is key for ensuring good crop growth and reducing the risk of diffuse pollution. The principal guides for calculating N application rates, including digestates are the SAC (Scottish Agricultural College) Technical Notes (TN651) for Scotland (SRUK, 2013), and the fertiliser manual RB209 (Defra, 2010) for England, Wales and Northern Ireland. The nutrient management software tools MANNER and PLANET are also often used to plan digestate applications. Digestate is classed as organic manure in RB209 and in a range of other guidance and legislation including Scotland's PEPFAA code of practice (Scottish Executive, 2005) and Nitrate Vulnerable Zones (NVZs). For digestates it is the readily available N (RAN) which is considered when calculating how much digestate to apply. It is estimated that approximately 80% of digestate N is available in the first year of application (WRAP, 2012a), showing digestates have high RAN.

In NVZs the maximum quantity of digestate which can be applied is based on a total N content of 250kg N/ha in any 12 month period (Natural Scotland, 2016) although the actual amount applied should not exceed the predicted crop requirement. UK whole and liquor food waste based digestates vary greatly in terms of their total N, spanning 2.9-6.9g N/kg based on reported data (Table 1). Food waste based digestates generally have more total N than slurry based digestates (WRAP, 2011a).

Table 1: Characteristics of whole and separated digestates from a range of UK sites on a fresh weight basis

Site	Feedstock	Fraction	Total solids (%)	Total N (mg/kg)	NH ₄ -N (mg/kg)	NO ₃ -N (mg/kg)	NVZ limit (t / ha digestate)
1	Food waste*	Whole	3.7	4900	3784	<0.1	51
2	Food waste*	Whole	4.5	6000	5260	<0.1	42
3	Food waste*	Whole	4.7	6200	6078	<0.1	40
4	Food waste*	Whole	4.2	5400	5010	<0.1	46
4	Food waste**	Whole	2.5	5876	3736	1.9	43
5	Food waste***	Whole	3.6	6912	6654	258.0	36
6	Food waste***	Whole	5.8	4327	4227	100.0	58
7	Food waste*	Liquor	2.9	3700	2990	<0.1	68
7	Food waste**	Liquor	2.8	4257	2547	4.2	59
8	Food waste & slurry*	Whole	3.8	5600	5590	<0.1	45
9	Potato waste*	Whole	2.2	2400	2039	<0.1	104
10	Cattle slurry, potato waste***	Whole	5.2	3359	2846	513.0	74
11	Chicken manure, cattle slurry*	Liquor	3.8	3900	2945	<0.1	64
12	Maize, cattle slurry, milk waste*	Liquor	7.1	4200	2044	<0.1	60
13	Maize*	Liquor	5.1	4100	2175	<0.1	61
13	Maize**	Liquor	5.3	3801	1601	4.9	66

*Dimambro (2015), digestate sampled in 2012; **WRAP (2015b) digestate sampled in 2013; ***WRAP (2015a)

Assuming an average food waste digestate total N content of 5g N/kg, one application of 50t/ha digestate would theoretically reach the NVZ limit for the 12 month period. However, to achieve the NVZ limit for a range of food waste digestates including potato waste, an application rate range of 36-104 t/ha is shown in Table 1. In general, lower digestate application rates will be appropriate, for example, where the amount of N in the digestate would exceed the crop requirement, or where the farmer is using a combination of digestate and other N sources.

Thus for the purposes of this project, the maximum annual load of food waste digestate in agriculture can be considered to be 70 t/ha, but could be as much as 100 t/ha where low N feedstocks such as potatoes are utilised. Even in areas not designated as NVZs, farmers should still follow the PEPFAA Code of Good Practice (CoGP) (Scottish Executive, 2005) which has similar recommendations to the NVZ regulations. Moreover the Cross Compliance Regulations (The Scottish Government, 2016) and the Controlled Activities Regulations General Binding Rules (SEARS and Natural Scotland, 2016), which apply across Scotland, must be adhered to.

The CoGP states that: *In all cases, application rates should not exceed the nutrient requirements of the crop or rotation. Surface applications of liquid wastes should not exceed 50 m³/ha at any single dressing. Solid wastes or injected wastes may be applied at higher rates provided there is no risk of pollution and crop nutrient requirements are not exceeded (whichever is lowest).*

2.2.2 How to apply digestate

Standard equipment which is used to apply raw slurry and separated liquid onto land can also be used to apply whole and liquor digestate, including tractor and tanker, self-propelled tankers or umbilical cord spreading (ADBA, 2013). Best practice is to apply digestate using a band spreader with a trailing hose or shoe, or a shallow injector (WRAP, 2012b). Applying digestate close to the plant roots in this way will increase the amount of nitrogen available to the crop, and reduce the amount lost to the atmosphere as ammonia gas compared to surface broadcast application (WRAP, 2012b). Where bandspreading or shallow injection equipment is not available, ammonia emissions (and odour nuisance) can be reduced by rapidly incorporating digestate into soils, ideally within 24 hours (Rollett et al., 2015).

The equipment used for spreading solid farmyard manure can be used for spreading separated digestate fibre, such as a broadcast spreader or dual purpose spreader (WRAP, 2011b). The advantages and disadvantages of these equipment types are summarised in a recent report (ADBA, 2013). From a physical contamination perspective, it would be reasonable to assume that distribution (and fate) in soil could be affected by application approach although no evidence has been found to confirm this.

To make optimum use of the N content of digestate it should be applied at times of active crop growth, which is generally during the early spring to summer period. For arable crops with an autumn N requirement, e.g. winter oilseed rape and leafy brassicas, digestate can also be applied in early autumn. For grass cut for silage, digestate, similar to other N fertilisers, should generally be applied after each cut, which may be up to three times a year in Scotland with recommended total

application rates of up to 310 kg N/ha (SRUC, 2013); in England up to six cuts a year are possible in intensive grass systems, with theoretical total annual application rates of up to 370 kg N/ha (Defra, 2010), which, using values from Table 1, could equate to 100-128 t /ha food waste based digestate or 168 t/ha potato waste based digestate.

2.3 Literature review results: The types and quantities of plastics within food waste and food waste derived digestates

Physical contaminants in digestates are generally categorised as plastic, rubber, metal, glass and ceramic, sand and stones, cellulosic materials (wood, paper) and ‘other’ (generally considered to be manmade materials) (Lukehurst et al., 2010, NRM, 2015). As plastic tends to be the most abundant (WRAP, 2016b) and visible (Al Seadi, 2002, Kräuter, 2015, Merkt, 2014) physical contaminant in digestate applied to land, this can cause a negative public perception of AD. In Scotland in 2013/14 the level of physical contaminants in food waste based feedstocks for AD (including sites which de-package) ranged from <1% to >10% on a fresh weight basis (Zero Waste Scotland, 2016). In contrast, food waste from German municipal biowaste bin collections containing 5% physical contaminants (including plastic) is deemed acceptable feedstock for AD (Kehres, 2015b), with AD operators being required to remove up to 99% of physical contaminants during processing.

The presence of physical contaminants in digestate, is highly dependent on their abundance in the original feedstock (Drosg, 2015) and the extent of the on-site separation (Al Seadi, 2002). Pre-processing of food waste-based feedstocks is common both to remove physical contaminants and to reduce feedstock size, with techniques including hand picking, de-packaging, screening, shredding and pulping (WRAP, 2014). Post-digestion processing in the AD industry includes using a screen, press or centrifuge. In the UK, for PAS110 digestates, separated liquor products with all particles < 2 mm do not currently require testing for physical contaminants (BSI, 2014).

2.3.1 *Measuring the amount of plastic in digestates*

There are currently two main approaches used globally to measure the amount of plastics in digestate.

In the UK, for PAS110 certified digestates, physical contaminants (as a group including plastics) are assessed using a weight based approach. The same approach (and method) is used for reporting physical contaminants in uncertified organic wastes spread to land in Scotland via a Paragraph 7 Exemption (SEPA, 2015). The digestate sample (whole, separated fibre or separated liquor) is wet sieved in order to separate out the stones that are >5 mm and physical contaminants that are >2 mm. After drying of the material retained on the 5 mm and 2 mm aperture sieves, physical contaminants are isolated, weighed and the results reported as kg/tonne on a fresh matter (FM) basis (NRM, 2015).

The current PAS 110 specification for digestate, updated by the Renewable Energy Assurance Ltd (REAL) in 2014 (BSI, 2014), is now set based on the total nitrogen content of the digestate, as shown in line 2 (100 %) of Table 2. QMS raised concerns on the limit for physical contamination allowed in digestate, saying that it was still too high for agricultural land. In their Assurance Scheme rules, both QMS and SQC have set a limit of 8% of the current limit of physical contamination (>2mm) by fresh weight, allowed under PAS110 (QMS, 2017, SQC, 2016).

SEPA will align their digestate physical contaminant limit to that used by QMS and SQC. This will be achieved using a phased approach with 50% of PAS110 levels by April 2017, 25% by April 2018 and 8% by April 2019.

Reporting to two decimal places, adjusted physical contaminant limits to 50, 25 and 8 % are shown in Table 2. It is important to note that keeping with a two decimal place limit does not allow discrimination of samples across the range of total N contents (this is further considered below as part of the work of this project).

Table 2: Adapted from PAS110 2014 showing current (100%) limits for physical contaminants (BSI, 2014) alongside new (50, 25 and 8 %) SEPA limits

Total N (%)	kg/t	<1	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9 or more
100%^a	kg/t	0.04	0.07	0.11	0.14	0.18	0.22	0.25	0.29	0.32	0.36
50%^b		0.02	0.04	0.06	0.07	0.09	0.11	0.13	0.15	0.16	0.18
25%^c		0.01	0.02	0.03	0.04	0.05	0.06	0.06	0.07	0.08	0.09
8%^d		0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03

^aCurrent PAS110 limits for physical contaminants in digestates based on digestate N content (grey shaded); Proposed SEPA limits to come into effect April 2017^b, April 2018^c and April 2019^d.

In terms of practice elsewhere, the German Institute for Quality Assurance and Certification (RAL) quality scheme has limits for physical contaminants (non-organic materials such as glass, plastics, biodegradable plastics, metals, rubber, bone fragments, paper and composite materials – excluding stones, volcanic and clay granules) in composts and digestates. The RAL quality scheme is managed by the German Compost Quality Assurance Organisation (Bundesgütegemeinschaft Kompost BGK).

Over 10 years ago RAL deemed the weight fraction limit of 0.5% DM for physical contaminants to be insufficient in discriminating materials with potentially high visual impact (due to low density, high surface area film plastics) from those with low visual impact (due to high density, low surface area 'rigid' plastics) following land application. Hence, in addition to the physical contaminant weight limit, optically measuring and reporting the surface area parameter was introduced in 2006, applied only to those composts or digestates that contained >0.1% DM physical contaminants (BGK, 2008).

The surface area method is now applied to all digestate samples, not just those with more than 0.1 % DM, with the RAL quality area limit for physical contaminants of 25 cm²/l of the fresh sample. (BGK, 2016). By July 2018, the surface area limit will be reduced to 15 cm²/l (Kehres, 2015b). Hence even composts or digestates that have a very low % DM plastic content may still fail the RAL surface area test as there is only little more than 29 mg of thin film / l digestate (LDPE, 12.5 µm thickness, density 0.94 g/cm³) required to exceed the 25 cm²/l limit.

In Germany, the legislation regarding fertilizers (DüMV, Düngemittelverordnung gesamt) has been amended with respect to foreign bodies (Anonymous, 2015) and will affect all fertilisers brought into circulation from 2017 onwards (Kehres, 2015a). The changes with regards to plastic contaminants are the following: Instead of the previous limit of a physical contaminant limit of 0.5% DM, the new limits distinguish whether physical contaminants belong in the 'non-degraded plastic films' category or the 'any other physical contaminants' category which also includes hard plastics. The new legal limit for non-degraded films is significantly reduced to 0.1% DM, while the new legal limit for any other physical contaminants is slightly reduced to 0.4% DM (Kehres, 2015a).

The term 'non-degraded plastic films' describes plastic film that, at the time of observation, has not yet degraded and has been caught by a sieving stage of 2mm. This term intends to include even biodegradable plastics, e.g. "Bio bin bags" that have not degraded. (Kehres, 2015a).

2.3.2 Types of plastic found in digestates

All common plastic polymer types are associated with food production and end use (Table 3) and therefore could potentially be found in digestate derived from food waste feedstocks. Typical food waste plastic contaminants are plastic films from materials such as polyethylene terephthalate (PET, e.g. oven proof films), high density polyethylene (HDPE, e.g. retail bags), vinyl or polyvinyl chloride (PVC, e.g. clear food packaging), low density polyethylene (LDPE e.g. frozen food bags), as well as other plastic films, including bags made from bioplastics such as polyhydroxybutyrate (PHB), polylactic acid (PLA) and thermoplastic starch (TPS) (Grundmann, 1983).

The precise characterization of polymers within plastic products enables greater understanding of the behaviour of the product in its overall life cycle, including when in the soil. On an industrial scale, a range of technologies are used to separate out plastics within materials recycling facilities (MRF) and mechanical biological treatment (MBT) systems, with the aim of obtaining groups of plastics for subsequent recycling. Air and rotational force are often utilised initially for the removal of plastic films and other flat items from a rigid mixed plastics fraction. Subsequently sorting whole rigid plastics is regularly achieved via cameras operating in the NIR and visible parts of the electromagnetic spectrum to achieve polymer or colour sorting, including sorting PP, PE, PET, PS and PVC (WRAP, 2008). The waste material in these systems is in a solid, dry state and so not directly comparable to the identification of plastics obtained from liquid digestates.

For identifying biodegradable plastics, there are a range of characterisation and degradation assessment methods. These include differential scanning calorimetry, atomic force microscopy, dynamic thermal analysis, gel permeation chromatography, and mass spectrometry as well as spectroscopy methods: nuclear magnetic resonance (NMR) and infrared absorption (IR) (Sikorska and Janeczek, 2014). However, there is no specific method used by the quality certification schemes to assess the type of plastic found in digestates, as it is only the total weight (and for RAL in Germany also the total surface area) of physical contaminants which is reported (BSI, 2014, BGK, 2015).

Simple chloroform tests can be used to identify compostable polymer fragments, or quantify the total amount of compostable polymer, present in a sample (Novamont Spa laboratory test method,

2016 pers comm), however this approach does not indicate the bioplastic polymer type (e.g. PLA, PHB, polybutyrate (PBAT) and polybutylene succinate (PBS)). The test can also give false positive results for polystyrene (PS) (Novamont, pers comm).

Table 3: Plastic types used in the food industry (IP, 2016), with details of properties (Anonymous, 2017) and density (Anonymous, 2016b)

Plastic group	Polymer type(s)	Uses related to food	General properties	Density (g/cm ³)
1	Polyethylene Terephthalate (PET) – most common polymer in the polyester family	Fizzy drink and water bottles. Salad trays, salad dressing bottles, peanut butter jars, ovenable film and prepared food trays.	Barrier to gas & moisture, heat resistant, clear, hard, tough, microwave transparency, solvent resistant	1.37-1.46
2	High Density Polyethylene (HDPE)	Milk, water, juice bottles; yogurt and margarine tubs, cereal box liners	Resistance to chemicals and moisture, hard to semi-flexible, strong, permeable to gas, soft waxy surface	0.93-0.97
3	Polyvinyl Chloride (PVC)	Clear food packaging	Excellent transparency, hard, rigid, resistance to grease, oil and chemicals, long term stability, low gas permeability	1.10-1.45
4	Low Density Polyethylene (LDPE)	Thick carrier bags, bread and frozen food bags, packaging films, squeezable bottles e.g. honey, mustard, some bottle tops	Toughness, flexibility, soft, good transparency, barrier to moisture	0.91-0.94
5	Polypropylene (PP)	Margarine and yogurt tubs, ketchup and syrup bottles, crisp bags, biscuit wrappers, microwaveable meal trays, most bottle tops	Resistance to heat, chemicals, grease and oil, barrier to moisture, hard but flexible, translucent, strong	0.90-0.92
6	Polystyrene (PS)	Yoghurt pots, fast food trays, foam hamburger boxes and egg cartons, vending cups, plastic cutlery	Clear to opaque, glassy surface, rigid or foamed, hard, brittle, high clarity, versatility, insulating	0.96 – 1.04
Other	Other: E.g. Nylon (PA) Acrylonitrile butadiene styrene (ABS) Polycarbonate (PC) Layered or multi-material mixed polymers	PC: Re-useable water and baby bottles	Dependent on resin or combination of resins	

Two techniques which may be used for laboratory based polymer type analysis are Fourier Transform Infrared Spectroscopy (FT-IR) and Raman spectroscopy. Both techniques generate a spectral fingerprint of the sample that can be compared to a database of known polymers or by identification of major peaks. Raman and FT-IR spectroscopy has been used to discriminate petro plastics (e.g. PE, PP) (Allen, 1999, Vianello, 2013). In addition, these techniques have used side by side to discriminate bioplastic polymers (e.g. PLA, PBAT, PBS and PHBS) (Cai and Feng, 2013).

2.3.3 The occurrence of plastics in digestates

No peer reviewed journal publications were found in English or German explicitly considering the quantity and/or type of plastics within digestates.

In terms of grey literature publications, (WRAP, 2011a) reported plastic as the only contaminant type in two food-based digestates in Wales, with 0.1 and 0.2 % DM plastic respectively. More recent work by WRAP (2016b) using the current physical contamination method (reporting on FM rather than DM basis) found all whole and separated liquor samples taken from two UK sites contained plastic contamination, with metal fragments found in a few samples. Despite all samples containing plastic contamination, a number of samples were below the reporting limit of 0.01 % kg/tonne FM. In terms of digestate product type, the separated liquor was more heavily contaminated than the whole digestate despite onsite screening of both products and the apparent smaller screen size of the separated liquor product.

Typical values for larger than 2mm physical contaminants (including plastics) in German digestates are within the range of 0-0.04% (BGK, 2015), with legal limits at 0.4% DM from 2017 (Kehres, 2015a, Kehres, 2015b).

A German study optically analysed the surface area of the physical contaminants of 1,116 compost and digestate samples using a scanner, and also assessed DM. Physical contaminant levels exceeded 0.1% DM in 504 compost and digestate samples (Thelen-Jüngling, 2006). The study found that only 8-9% of the total number of samples exceeded the contaminant limit with a surface area of more than 25 cm²/l fresh sample, while the majority of samples were below this level. The report does not include details of the types of physical contaminants found.

A range of articles regarding the quantity of organic compounds and persistent organic pollutants (POPs) in digestates were found during the course of the literature review, published in English (Amlinger et al., 2004, Longhurst et al., 2012, WRAP, 2011a, WRAP, 2016a) and German (Grundmann, 1983, Kupper et al., 2007, Kupper et al., 2008, Stäb, 2011). Although this topic is beyond the remit of this project, it should be considered that some of these organic compounds potentially originate from plastics.

2.4 Literature review results: The effect of plastics on soil quality/function and crop health/growth.

Measuring soil quality is a key factor in the assessment of the effects of applying digestates to arable and grassland systems. Indeed, a Swedish review of digestate use in agriculture highlighted the need for monitoring to detect early perturbations in soil quality (Arthurson, 2009).

When considering soil quality in arable and grassland soils, a range of physical, chemical, and biological properties of the soil can be considered, hence the standard soil characteristics measured are discussed below. Subsequently, studies regarding the use of plastics in agriculture, impacts of plastics on soil quality and finally digestate use in agriculture are discussed.

2.4.1 Measuring soil quality

The soil characteristics to measure when assessing arable and grassland depend on the location and the purpose of the assessment, as shown in Table 4. For example, for organic amendment application, including digestates, trial work usually focuses on a combination of chemical properties including soil nutrients and potentially toxic elements (PTEs) in addition to physical measurements (WRAP, 2016a). The SEPA Paragraph 7 Exemption for the beneficial application of organic wastes to land stipulates that soils must be tested for pH, nutrients, carbon and PTEs (SEPA, 2015).

Table 4: Commonly studied soil quality indicators, including general parameters to assess soil quality (G), standard UK agricultural soil tests (A), and parameters used to assess organic materials spread to land (O) (Cundill et al., 2012, Defra, 2010, Lewandowski and Zumwinkle, 1999)

Chemical Measurements	G	A	O	Physical measurements	G	A	O	Biological measurements	G	A	O
Total carbon & nitrogen	✓	✓	✓	Particle size	✓			Microbial biomass	✓		✓
Mineral nitrogen (nitrate, ammonium)	✓	✓	✓	Rooting depth	✓			Earthworms	✓		✓
P, K, Mg (S, Ca)	✓	✓	✓	Bulk density	✓		✓	Basal respiration	✓		
Plant micronutrients			✓	Soil texture		✓		Active nitrogen	✓		
Cation exchange capacity	✓			Water infiltration / hydraulic conductivity	✓			Total organic carbon	✓		
Extractable bases	✓			Aggregate stability	✓						
pH	✓	✓	✓	Water holding capacity	✓		✓				
Electrical conductivity	✓		✓	Aggregate size	✓						
Sodium adsorption ratio	✓			Penetration resistance	✓						
Organic matter	✓	✓	✓								
PTEs			✓								
Organic contaminants			✓								

Other parameters measured during organic amendment field studies related to the soil are nitrate leaching and gaseous emissions from the soil including ammonia, methane and nitrous oxide (Cundill et al., 2012).

Therefore, assessment of the impact of plastic contamination on soil quality should include the analysis of one or more of these quality indicators. Examples of articles on the application of soil quality indicators to plastic contaminants in soil are provided below (section 2.4.3).

2.4.2 Other sources of plastics in agriculture

Plastics are being used to improve soil properties and crop production both in agriculture and in field horticulture. Scotland has 6.2 million ha of agricultural land including 19,400 ha of land used for horticultural production (Anonymous, 2016a). The vast majority of Scottish horticultural land is used

for producing vegetables for human consumption (16,700) with fruit grown on 1,800 hectares and flowers and nursery stock on 950 hectares. Plastic mulches and fleeces are used in both conventional and organic vegetable and fruit farming in Scotland (SOPA, 2009, Sutton, 2000), and have recently been considered for maize production (AHDB Dairy, 2014). A recent review of plastic mulching in agriculture highlighted that adverse effects may arise from plastic additives, with plastic residues likely to fragment into microplastics but remaining chemically intact and accumulating in soil where they can successively sorb agrochemicals (Steinmetz et al., 2016).

Each year Scottish agriculture gives rise to about 20,000 tonnes per year of non-packaging plastic wastes including plastic mulch film, silage plastics and greenhouse or tunnel film (Scottish Executive, 2004). These products contain a range of plastics including, polyolefin, polyethylene (PE), Polypropylene (PP), Ethylene-Vinyl Acetate Copolymer (EVA), PVC and, less frequently, Polycarbonate (PC) and poly-methyl-methacrylate (PMMA) (Anonymous, 2016e).

In Germany, a number of polymer-based products are available for use in field horticulture, including polystyrene foam with closed pores ("Styromull") which can be used to improve aeration of soil (Anonymous, 2016d), and an open-pored foam resin based on polyurethane ("Hygromull") which is used to improve water retention (Anonymous, 2016c). Synthetic superabsorbent soil conditioners based on cross-linked acrylamide and acrylic acid copolymers are proposed to increase water storage capacity of the soil in brownfield sites and forestry due to their ability to decompose in soils (Wolter et al., 2002).

Plastics such as Hygromull are applied on field vegetables in Germany at rates of up to 20l/m² (Anonymous, 2016c), which corresponds to about 4400kg/ha. In comparison, application rates of plastic through digestates, slurry and compost on agricultural land in Germany can legally reach up to 100kg/ha over a time period of three years (Klement, 2016).

A well-known plastic based soil conditioner that has been researched since the 1950s is anionic polyacrylamide (PAM), which is used in agriculture to enhance filtration (Sojka, 2007), reduce surface sealing and crusting, and reduce erosion (Green and Stott, 1999). In 2007, it was highlighted that about 800,000 ha of US irrigated land used PAM for erosion and/or infiltration management (Sojka, 2007). It is known that one constituent of PAM, monomeric acrylamide, is neurotoxic and carcinogenic in humans and animals. However, as long as the acrylamide monomer content is low, it is deemed an acceptable level for the environment (Wolter et al., 2002). The product typically contains 0.1% acrylamide monomer.

Agricultural seed coatings include colorants, binders, polymers and other additives. A range of compounds are used in binders which includes various starches, sugars, cellulose, vinyl polymers, clay, gum arabic, and others (FMI, 2017). Moreover, water soluble plastic polymers are used in agriculture for seed coatings (Anonymous, 2002).

2.4.3 Literature on impacts of plastic on soil quality/function and crop quality

Recent publications highlight the need for investigating the impact of plastic on soil quality and function, crop health and growth (Klement, 2016, Stöven et al., 2015). Despite this, research on

plastic contamination in terrestrial environments is currently lagging behind that in marine environments (Rillig, 2012)

At the time of writing, a handful of journal articles have been found relating to the impact of plastic on the soil environment. A couple of these are perspective pieces (Nizzetto et al., 2016, Rillig, 2012); however, at least two primary research articles present data on issues related to ageing and toxicity of plastics in the environment. Mosnáčková et al. (2016) looked at ageing of PLA/PHB blended film mulches in soil together with the assessment on the yield and quality of sweet pepper production. These authors found that the film aged both in soil and under sunlight exposure. In terms of crop effects, the film had no effect on sweet pepper yield and quality. Lwanga et al. (2016) looked at the effect of LDPE microplastic on earthworm (a biological soil quality indicator) fitness and survival. The study found that earthworm growth was lower and motility was higher in soils with <2 mm microplastic at ≥ 28 % w/w compared to soil with 7 % w/w microplastic and the control (0 % w/w). Although the assessment of the impact of microplastics <2 mm on the environment is beyond the scope of this project, this second article is likely to be the start of a growing field of research in recognition of these emerging contaminants.

While it can be argued that any plastics found in food waste based digestate would be mainly plastics approved for food containers that should pose negligible risk to human health, there are considerations that highlight the need for further research in the following areas:

- Plastic in the soil may become a food source for organisms (e.g. mealworms digesting polystyrene (Yang, 2015)) with metabolic effects just starting to be researched.
- Contact of certain plastics with organic constituents in soil, such as humic acids, may accelerate the leaching of plastic softeners or other POPs (Deventer et al., 2004)
- Plastic particles may become a microbial habitat for potentially harmful soil organisms (McCormick et al., 2014, Stöven et al., 2015)
- Leachates from certain plastics may act as hormones that have the potential to interfere with soil organism, plant and human biology (Kunz, 2011)
- Additives in plastics, including phthalic acid esters commonly associated with PVC, may be toxic to soil microbes and affect enzyme activity (He et al., 2015).
- Decomposition of certain plastics results in microparticles that remain in the environment with unknown effects (Klement, 2016, Stöven et al., 2015).
- Decomposition of certain plastics results in nanoparticles that may have undesirable effects on anaerobic as well as aerobic decomposition processes (Reihlen and Jepsen, 2015).

2.4.4 Literature on digestate use in agriculture (physical contaminants)

There are a range of studies on the application of digestates to agriculture (Table 5). These tend to focus on a comparison with standard fertilisers and investigating the agronomic aspects of crop production including assessments of crop establishment, growth and yield, nitrogen mineralisation, soil quality and biological activity. There were no studies identified that compared the effect of digestate application with and without plastic contaminants, neither in the short term nor in the long term. Moreover, the studies found did not report on the presence of plastics or other physical

contaminants in the digestates, whether the digestate was produced from food waste, crops or other inputs. There have been studies on the impact of plastic enrichment of composts on soil structure, fertility and plant growth (Atuanya, 2012) however this is outside the scope of this report which is specifically reporting on plastic that has undergone the AD process.

Table 5: Digestate use in agriculture, example of studies

Amendments / treatments	Project duration	No. of sites	Crops	Assessment criteria	Reference
Compost and digestate	2 years	1	Maize	<i>Pythium ultimum</i> , <i>Rhizoctonia solani</i> , respirometric and enzyme activity	Fuchs et al. (2008)
2 digestates, unfertilised control	1 year	2	Maize	Crop growth, soil pH, total N, P, K, Mg and Ca, fluorescein diacetate activity and dehydrogenase activity	Kupper et al. (2007)
Digestates (maize/ slurry), rapeseed pressings, cow and pig slurry, green/food waste compost, horse manure, conventional fertiliser	7 years	2	Maize	Yield, lifecycle analysis of on-farm AD	Rippel et al. (2008), Wendland (2009)
5 digestates (slurry co-digested with food waste), slurry control	2 years	1	Winter barley, winter wheat	Yield	Brenner (2008)
Digested slurry, slurry, slurry with standard inorganic fertilisers	7-20 years	4	Winter barley, spring barley, maize, mustard, Lucerne	Micro, meso and macrofauna, water content, water capacity, soil density	Petz (2000)
Manure, cattle slurry, digested cattle slurry, cattle slurry co-digested with crops	2 years	1	Winter wheat, spring wheat, potatoes, winter rye, peas, spelt, clover	Yield, N-uptake, N-losses, P, K, Mg, greenhouse gas emissions and soil organic matter	Möller et al. (2006)
3 digestates (cattle slurry, crops), inorganic fertiliser, unfertilised control	2 years	1	Spring wheat, maize	Yield, soil microbial activity, respiration, worms	Sensel (2008)
Compost, digestate (biowaste) - artificial fertiliser straights were used to balance and top up to the crop nutrient requirement	2 years	5	Spring wheat, winter wheat, barley, grassland	Interaction of weather, soil, fertiliser and plant, nutrient release, SOM	Heslop and McCabe (2012)
Raw and digested wine processing waste water, olive pomace compost, commercial fertiliser, unfertilised control	3 years	1	Lettuce	Yield, leaf nitrate, soil mineral N	Montemurro et al. (2010)
Digestate (kitchen waste), Cattle manure, NPK fertiliser	2 years	1	Spinach, komatsuna	N uptake, leaf nitrate, fertilizer value. <i>Escherichia coli</i> , fecal streptococci and <i>Vibrio parahaemolyticus</i> concentrations in digestate, soil and plant leaves	Furukawa and Hasegawa (2006)

2 digestates (wine waste water; food processing), mineral fertilizer	2 years	1	Permanent alfalfa	Yield, organic matter, crude protein and neutral detergent fibre digestibility	Lestingi et al. (2012)
Digestate (slurry and agricultural residues), cattle slurry, mineral N	3 years	1	Grassland	Yield, economic value	Kall et al. (2016)

In 2013, a UK literature review identified only 167 publications specifically on the use of digestate (all feedstock types including sewage sludge), with 75% of the research focussing on the agricultural sector (WRAP, 2013). Of these, desk studies, bench trials (the AD process and digestate analyses) and pot trials were predominantly found, with some field trials. None of the studies mentioned therein, which included some digestates from food waste, included the effects of physical contaminants in digestates on soil quality. More specific studies were recommended by the authors and also by others, to address large knowledge gaps by advancing knowledge on digestates and their contribution to a sustainable and environmentally sound agriculture. These current identified gaps include the linkage between the nature of the feedstock and the amending properties of digestates, the long-term effects of digestate applications on soil chemical and physical properties (Nkoa, 2014), long term ecological effects (Fuchs et al., 2004), the effect of alternative application strategies on soil properties and timing effects of digestate application in crop rotations, effects on plant pathology and crop yield (Fuchs and Schleiss, 2009). Interestingly, none of these recommendations included exploring the fate of physical contaminants derived from digestates applied to agricultural land.

In general, studies regarding the potential contaminants of organic fertilisers including digestates focus on heavy metals, organic compounds and pathogens both for soil quality (Longhurst et al., 2012, Monteiro et al., 2011) and impacts on human health (Anonymous, 2013). For example, in a recent long-term UK study entitled 'Digestate & compost in agriculture project' (DC-Agri), physical contaminants were not studied in the organic amendments or in the soil, only PTEs and POPs (WRAP, 2016a). The study observed that repeated digestate applications (both food and manure-based) improved the soil nutrient status, leading to higher crop yields.

A range of non-UK studies were identified where digestate was used and generally compared to other organic amendments or inorganic fertilisers, with some examples provided in Table 5. However, studies including effects of plastics derived from digestates on soil quality and crop parameters were not found.

A WRAP project that was commissioned in 2011 entitled 'Soil quality impacts of physical contaminants in digestate and compost' was not published (McManus, 2016 pers comm). However it was reported that this was a *'review of scientific literature on the impact on soil quality of "accepted" physical contaminants (ie <2mm) in BSI PAS 100 composts and BSI PAS 110 digestates. The review had a particular focus on small plastic fragments and their impact on soil physical properties and soil fauna. This review confirmed that there was little relevant literature'* (WRAP, 2013).

2.5 Literature review: Conclusions and further work

CONCLUSIONS

Food waste digestate application in agriculture

- There are three types of digestate (whole, liquid and fibre), with whole digestate being the most commonly available in Scotland
- In UK agriculture, optimising the quantity of nitrogen (N) to apply in agriculture (including from inorganic fertilisers and organic manures such as digestate) is key for ensuring good crop growth and reducing the risk of diffuse pollution

The types and quantities of plastics within food waste and food waste derived digestates

- The presence of physical contaminants in digestate is highly dependent on their abundance in the original feedstock (Drosg et al., 2015) and the extent of the on-site separation (Al Seadi, 2002).
- All commonly recognised plastic types are associated with food production and end use (Table 3) and therefore could potentially be found in digestate produced from food waste. Typical food waste plastic contaminants are plastic films from materials such as polyethylene terephthalate (PET, e.g. oven proof films), high density polyethylene (HDPE, e.g. retail bags), vinyl or polyvinyl chloride (PVC, e.g. clear food packaging), low density polyethylene (LDPE e.g. frozen food bags), as well as other plastic films, including bags made from bioplastics such as polyhydroxybutyrate (PHB), polylactic acid (PLA) and thermoplastic starch (TPS) (Grundmann, 1983).
- There are currently two main approaches used globally to measure the abundance of plastics in digestate. In the UK, for PAS110 certified digestates, physical contaminants (as a group including plastics) are assessed using a weight based approach. The German Institute for Quality Assurance and Certification (RAL) deemed the weight fraction limit of 0.5% DM for physical contaminants to be insufficient, due to low density, high surface area film plastics having the potential to dominate the visual appearance once the compost or digestate is applied to the field. Hence, in addition to the physical contaminant weight limit, optically measuring and reporting the surface area parameter was introduced in 2006, applied only to those composts or digestates that contained >0.1% DM physical contaminants (BGK, 2008).

The effect of plastics on soil quality/function and crop health/growth

- In the UK there is a range of guidance available on the use of digestates in agriculture; however, no published research on the abundance or distribution of plastic contamination within soils currently exists. In fact, no published industry method exists currently for the analysis of physical contaminants (and plastic specifically) in soils.
- There is limited literature on risk of plastic polymers on soil quality and crop function. Lwanga et al., (2016) found that higher concentrations of LDPE microplastic particles had a negative effect on earthworm growth and survival. However, further studies are needed to

be able to fully assess the risks of this and other polymer types. The body of literature is likely to grow in the next few years with growing research on microplastics in terrestrial environments.

- Plasticizers associated with plastic polymers, such as phthalates and PVC, are known to be toxicants.

FURTHER WORK

- The impact of plastic contaminants in agricultural soil as a result of biosolid or compost application may be broadly comparable to that of digestates, and more research has been undertaken worldwide on compost application to agriculture as compared to digestates. Hence it is recommended that a comparable literature review could be undertaken on biosolids and composts.
- A general literature search considering the potential contaminants (e.g. plasticizers such as PCB, DEHP, DBP) which could arise from these plastics, and their likely impact, may be useful in identifying further research requirements.

3.0 Materials and Methods

This section outlines the materials and methods used to address objectives 2 and 3 outlined in section 1.0 of the report.

3.1.1 Digestate sampling

Digestate samples were collected from three PAS110 certified UK merchant-fed AD sites at the end of August (Site 1) and October (Sites 2 and 3) 2016. The sites varied in whether or not they had front and back end processes (discussed in the results section). Further samples were collected and processed in 2015 from a fourth PAS110 certified AD site (site 4) as part of independent research work on plastics in digestates. Sampling for all four sites was carried out as previously reported (WRAP, 2016b). Following collection, digestate samples were weighed on a calibrated 2 decimal place (dp) balance and processed as detailed below.

3.1.2 Digestate sample processing

Digestate samples were processed using the current PAS110 physical contaminant method (NRM, 2015) with minor modification to support supplementary fragment processing and analysis. Specifically, fragments from each digestate sample were recovered from the 2 mm sieve immediately after washing and laid out onto the base of one or more plastic Petri dishes. This

approach was found to minimise the number of fragments moving position due to static charge and helped ensure fragments were flatly presented for scanning (section 3.1.5).

3.1.3 Soil sampling

Soils were sampled from a UK site in December 2016 with the view to developing a baseline understanding of the amount of plastic in soils with and without food waste based digestate application. The specific site was selected based on the availability of both arable and grassland fields with multiple PAS110 certified digestate applications and corresponding control fields with no history of digestate application. Further, previous analysis by us of the actual digestate applied at this site was also considered beneficial to help us interpret the results. Basic details of the fields, cropping, cultivation and digestate application histories are shown (Table 6).

Table 6: Land use, cultivation and digestate application histories of the four sampled fields

Field	Cropping history	Cultivation	Digestate application history
1	Arable (2013 – wheat, 2014 – peas, 2015 – wheat, 2016 – wheat)	Annually	Yes. 3x 2013, 3x 2015, 2x 2016. Between 9-20 t/ha per application
2	Arable (2013 – wheat, 2014 – oilseed rape, 2015 – wheat, 2016 – peas)	Annually	No
3	Permanent grassland	None for +10 years	Yes. 20 t/ha for last four years
4	Permanent grassland	None for +10 years	No

Samples were taken from five locations in each of the four fields at depths of 0-5, 5-15 and 15-25 cm. A ~200 cm² sample was taken from 0-5 cm depth using a stainless steel spade (wiped clean between each sample). A hollow hand auger (internal diameter 14 mm) was used to sample at the same location to a depth of 25 cm. Each auger soil core was split half way to achieve the two separate samples from ~5-15 and ~15-25 cm depth respectively. The auger was chosen as an efficient sampling method to investigate potential transfer of plastic fragments through the soil profile with and without cultivation.

3.1.4 Soil sample processing

Initially, a dry sieving approach was considered; however, due to the texture (high clay content) of the specific samples collected and general fragile nature of plastic (especially film) fragments this was abandoned in favour of a wet sieving approach.

The effectiveness of a wet sieving approach was trialled using virgin film (HDPE and PLA) fragments prepared by cutting squares approx. 3 x 3 mm. Ten fragments were 'spiked' into 25 g fresh weight of soil and mixed with a metal spatula. The samples were then applied to a 200 mm diameter sieve with 2 mm aperture and washed with tap water. Fragments were recovered and counted. The procedure was repeated five times each for HDPE and PLA and recoveries were 98% and 96 % respectively.

The approach confirmed, each 5-15 and 15-25 cm depth soil sample was placed individually on a 2 mm aperture sieve and washed with a restricted flow hose attachment. The sieve was inspected regularly through the washing process for fragments which could fold, curl or break and subsequently fall through the 2 mm aperture. Assisted breaking of soil clumps was kept to a minimum to prevent potential plastic fragment damage (some fragment types known to be fragile from the digestate work) with the sieve observed throughout this process. Slight modifications were adopted for the larger 0-5 cm arable and grassland samples with plant material. For the arable samples, stubble and grain husks were initially removed by water based density separation prior to sieving. For the grassland samples, the sward was pulled apart by hand and inspected plant matter removed before sieving. Any suspected plastic fragments recovered were placed in plastic Petri dishes for subsequent processing as outlined in sections 3.1.5 and 3.1.6.

3.1.5 Plastic fragment weight, surface area and size determination

Petri dishes containing plastic fragments recovered from both digestates and soils were scanned using a standard desktop scanner with two scans performed per plate; one with a white and one with a black background. The images were autocorrected using Microsoft Office Picture Manager Software to improve clarity for image processing and saved as JPEG files.

Scan images were analysed using ImageJ 1.48v software (National Institutes of Health, USA). Analysis was set to include surface area and bounding rectangle measurements. The latter was used to assess the 'shape' of fragments in terms of rectangle length and width. Images were scaled using the known Petri dish diameter.

Black background images were converted to binary and fragment 'holes' filled using software auto functions. The 'wand' tool was then used to select individual fragments and add them to the software ROI manager. Original black background image was viewed alongside the binary image during fragment picking. Fragments on the binary image not matching their counterparts on either the black or white background images were instead manually outlined using the 'polygon' tool. The measured fragments were then transferred to Microsoft Excel or IBM SPSS Statistics 24 for further handling and processing.

Plastic fragments were left to dry at ambient temperature before transferring to aluminium dishes to reduce vessel static charge for weighing. Total fragment weight per sample was determined using an analytical balance reporting to 4 decimal places (dp).

Fragments for each selected digestate and all soil samples were transferred to 96 well microtiter plates with individual numbered wells for cataloguing and storage prior to determining polymer type.

3.1.6 Analysis of plastic fragment polymer type

Screening of fragment polymer type was carried out by FTIR using a Thermo Scientific™ Nicolet™ iS5 spectrometer fitted with iD7 attenuated total reflectance (ATR) accessory with Diamond KBr plate. The instrument was controlled and spectra captured/interpreted using the Thermo Scientific™ Omnic 9.2.106 software.

Samples were measured in transmission mode in a wavenumber range of 4000-400 cm^{-1} . Spectra were generated by averaging of 16 scans with a resolution of 4 cm^{-1} . A background was measured with the same parameters against air.

Assignment of fragment polymer type was based on comparison to the Hummel Industrial Polymer reference library. Further interpretation of results was supported by comparison to reference spectra of known available polymer materials.

For digestate derived fragments, three samples were chosen at random from each of sites 1-3. Results are presented as % of total fragment number found in the three individual samples from each individual site.

For soils, all recovered fragments were analysed.

4.0 Results and Discussion

4.1.1 Weight of plastic in digestate products

Following the PAS110:2014 physical contaminant method, plastic fragments were recovered from all digestate samples collected. Although only plastic fragments were analysed in this project, glass, metal and paper were observed in some samples which would have added to the reported physical contamination weight.

For plastic only contamination therefore, the results clearly show that samples from site 1 were the most heavily contaminated (Table 7). The lower amounts of plastic contamination in sites 2-4 was either due to post digestion screening alone, high selectivity in terms of feedstocks or both of these. Site 2 had no post digestion screening instead relying on the selection of feedstock alone, whereas, sites 3 and 4 both operated post digestion (≤ 2 mm) screening.

Working to two dp, in line with current PAS110 physical contaminant reporting requirements, samples 8 and 14 from site 2 and samples 2 and 6 from site 4 were below the reporting limit.

Given the proposed new SEPA physical contaminant limits displayed in Table 2, and assuming a digestate N content of at least 3 % (based on our literature review), all samples from sites 2-4 were below April 2017 and 2018 limits of 0.07% and 0.04% respectively..

Table 7: Plastic contamination in individual digestate samples reporting as currently required by PAS110:2014

Sample	Plastic contamination (% kg/tonne FM)			
	Site 1	Site 2	Site 3	Site 4
1	0.16	0.03	0.02	0.01
2	0.09	0.01	0.01	<0.01
3	0.39	0.01	0.01	0.01
4	0.17	0.01	0.01	0.02
5	0.24	0.01	0.01	0.01
6	0.23	0.01	0.03	<0.01
7	0.28	0.01	0.02	0.01
8	0.12	<0.01	0.01	0.02
9	0.35	0.01	0.01	0.02
10	0.28	0.01	0.01	0.01
11	0.14	0.01	0.01	0.01
12	0.22	0.01	0.01	0.02
13	0.30	0.01	0.01	0.01
14	0.37	<0.01	0.02	0.02
15	0.25	0.01	0.03	0.01

Given the physical contaminant limits for PAS110 samples are set based on total N content, 8 % (April 2019) physical contaminant limits considered to 3 as well as 2 dp (Table 8).

Table 8: Adapted from PAS110 2014 showing SEPA 8% (April 2019) limits to both 2 and 3 dp for physical contaminants

Total N (%)	kg/t	<1	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9 or more
8% 2dp	kg/t	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03
8% 3dp		0.003	0.006	0.009	0.011	0.014	0.018	0.020	0.023	0.026	0.029

Results for site 3 show how individual samples potentially failing on a 2 dp limit may in fact pass when reporting to 3 dp (Table 9). This can be demonstrated for site 3 sample numbers 1 and 14 if the N content is assumed to be within the range 5.0-5.9 kg N/tonne (dark grey shaded).

Table 9: Plastic contamination in individual digestate samples from sites 2 and 3 reporting to both 2 and 3 dp

Sample	Plastic contamination (% kg/tonne FM)			
	Site 2		Site 3	
1	0.03	0.031	0.02	0.015
2	0.01	0.007	0.01	0.012
3	0.01	0.007	0.01	0.007
4	0.01	0.011	0.01	0.013

5	0.01	0.006	0.01	0.009
6	0.01	0.005	0.03	0.034
7	0.01	0.008	0.02	0.020
8	<0.01	0.004	0.01	0.013
9	0.01	0.007	0.01	0.013
10	0.01	0.009	0.01	0.015
11	0.01	0.014	0.01	0.007
12	0.01	0.008	0.01	0.015
13	0.01	0.009	0.01	0.011
14	<0.01	0.003	0.02	0.015
15	0.01	0.009	0.03	0.032

Using data from both Tables 7 and 8 indicate that samples from site 2 were the cleanest in terms of plastic contamination weight. However, this of course only reflects the digestate produced on the day of sampling, and does not consider the presence of other non-plastic physical contaminants.

4.1.2 Plastic fragment number, surface area and fragment shape in digestate products

In support of the weight based results, the number of isolated (and assumed) plastic fragments was greatest for site 1, which totalled 2,505 in 15 discrete ~ 1 litre size samples (Figure 1). This compares with 338, 557 and 765 in sites 2-4 respectively (Figure 1). Similarly the mean surface area of plastic fragments was greatest for site 1 at 0.33 cm² compared to the other three sites with values ≤ 0.18 cm² (Figure 1).

In terms of fragment shape, there appears (on visual appearance only) no difference in the pattern of fragment shape at different sites (Figure 2). This figure clearly illustrates that site 1 has a greater number of fragments with the largest recovered fragment at just over 36 x 32 mm (3.6 x 3.2 cm) in size. Although there appears no obvious difference visually, further statistical analysis would be required to fully explore these results.

Figure 2 also shows that fragments smaller than 2 mm (in one or both measures) can be captured on the 2 mm sieve. This can be most clearly seen in the site 2 and 4 graphs.

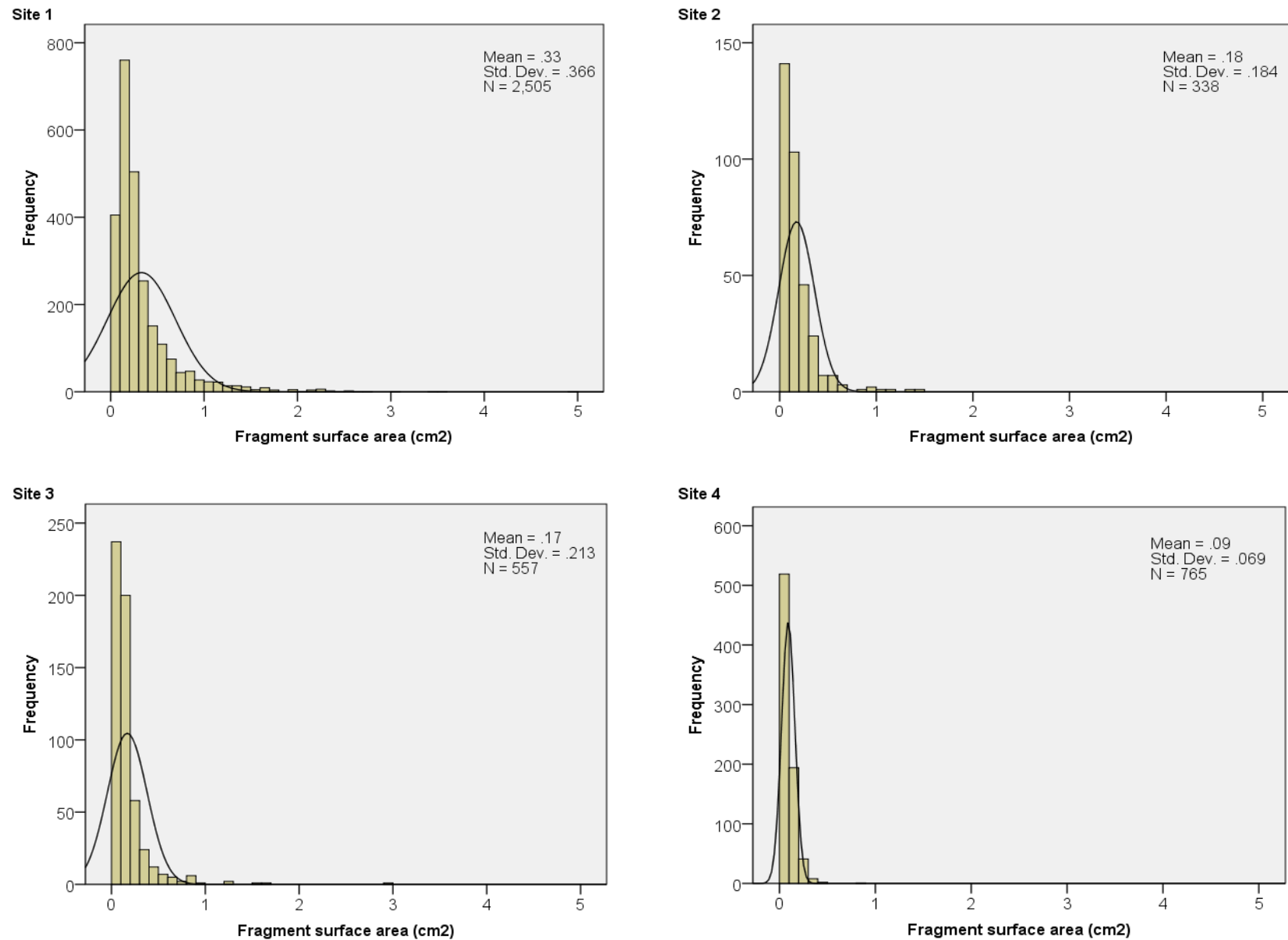


Figure 6: Histograms of plastic fragment surface area isolated from 15 discrete digestate samples from sites 1-4

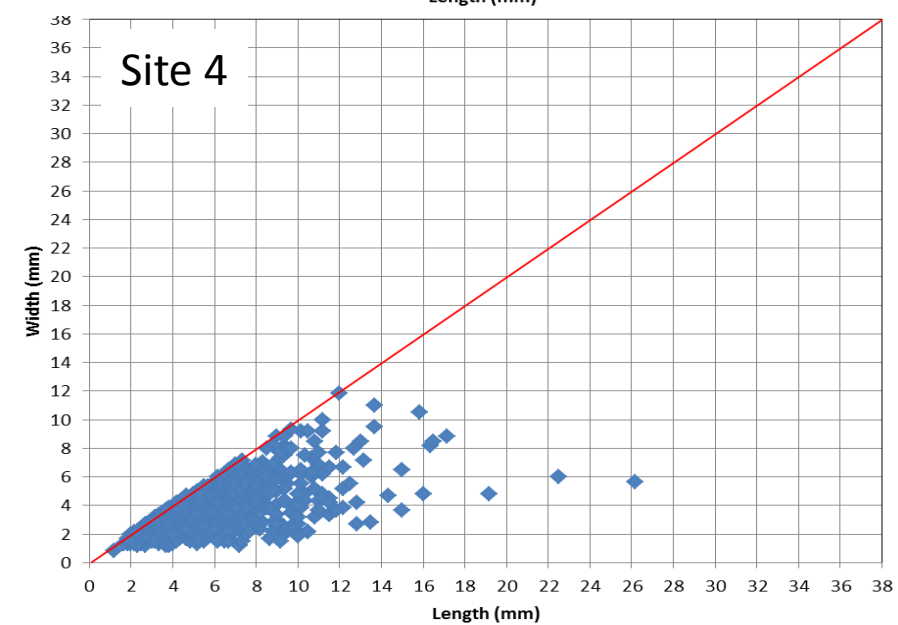
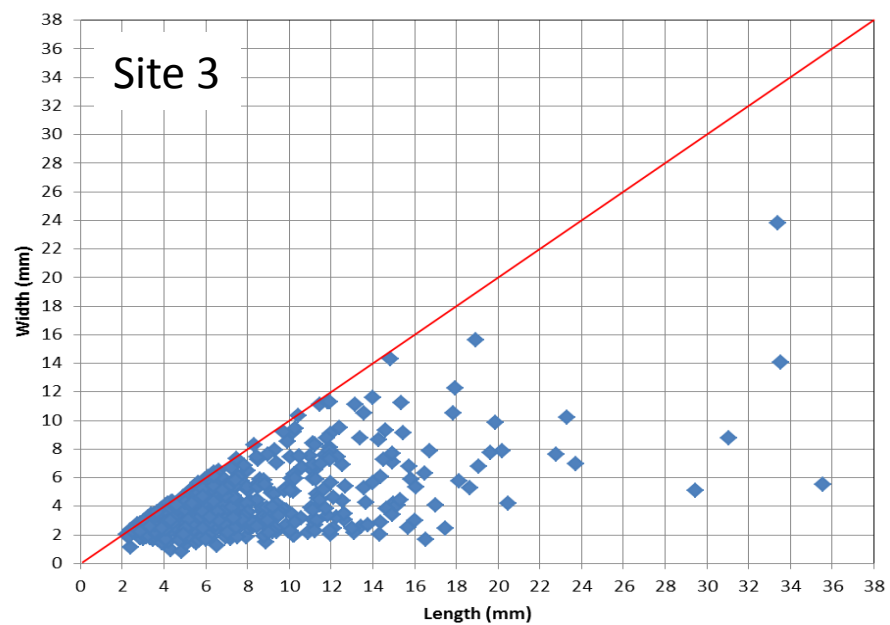
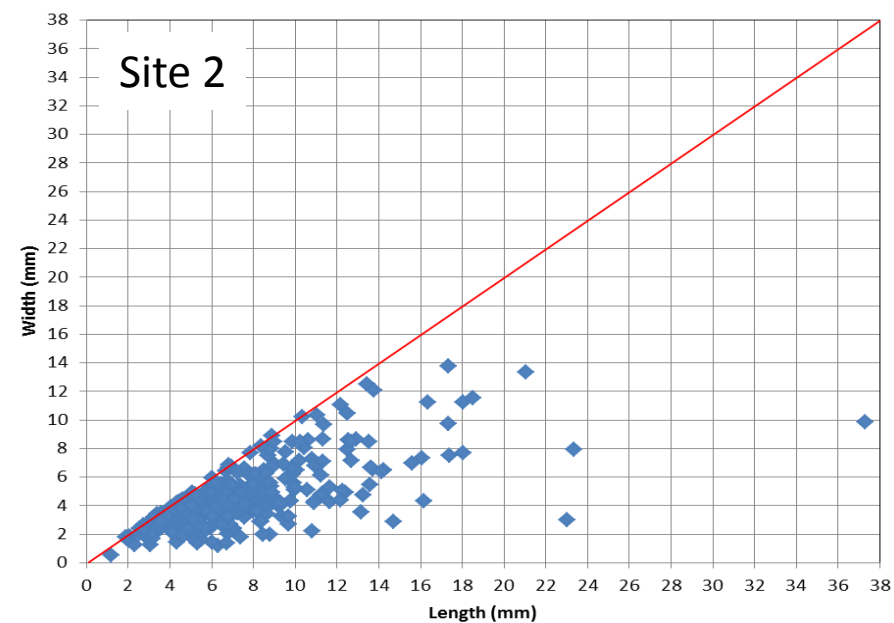
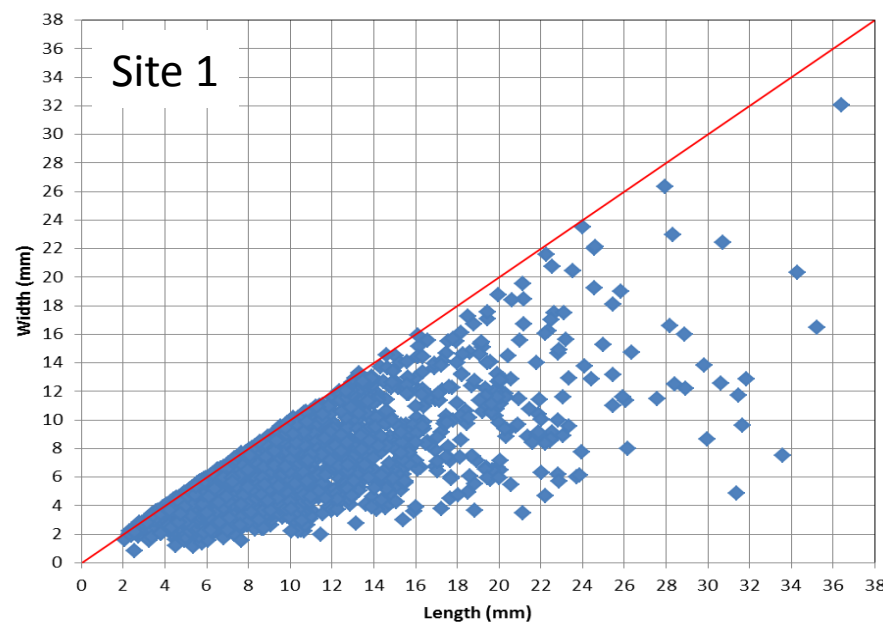


Figure 2: Scatter plots of isolated plastic fragment 'shape' from 15 discrete digestate samples for sites 1-4

4.1.3 Plastic fragment surface area and weight correlation

Building on the WRAP 'Physical contaminants in PAS composts & digestates' project (WRAP, 2016b); further consideration was given in this project to the potential use of a surface area measure to determine abundance of plastic contamination in digestates. In considering this, total plastic fragment weight and surface area data for individual digestate samples were compared.

Although a strong surface area to weight correlation ($R^2 = 0.9386$) is achieved when considering site 1-3 data collectively, it is obvious from figure 3 that site 1 samples (circled in red) greatly bias this. Given the high amount of plastic fragments, it is unlikely a surface area measure would be required for site 1 samples specifically as the weight based approach alone would appear adequately robust. In addition, for commercial laboratories, samples with these quantities of plastic would be labour intensive to process and therefore would likely have a negative effect on derived analytical costs.

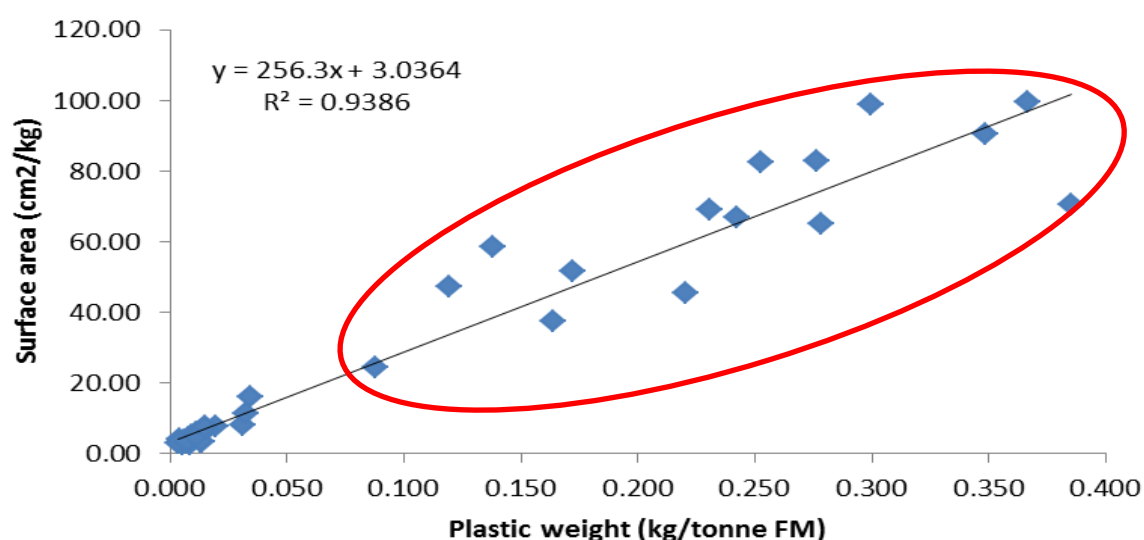


Figure 3. Correlation of individual digestate sample plastic contamination surface area to weight using Site 1- 3 data. Site 1 samples only within red circle.

Further analysis was carried out using data from sites 2-4 which (broadly speaking) span the critical limits for implementation by SEPA in April 2019 (Figure 4). In particular the figure shows the majority of data points for all three sites fall between the critical weight limits of 0.003 and 0.020 kg/tonne FM (extrapolating Table 2 values to 3 decimal places and assuming total N content less than 7 % based on Table 1 data). As such the figure gives a reasonable indication of where comparable surface area limits may lie.

Due to potential for some under and over-reporting with handling and/or analysis of fragments, the direct substitution of weight for surface area methods and limits is unadvisable. However, a surface area measure may complement the weight determination method, particularly in respect of the proposed April 2019 limits. In short the surface area method can distinguish samples with a

genuinely high abundance of ‘film’ plastic from those with a small number of heavier ‘rigid’ fragments (WRAP 2016b). In terms of visual perception, the surface area method may add a means of quantifying the visual impact on the soil surface.

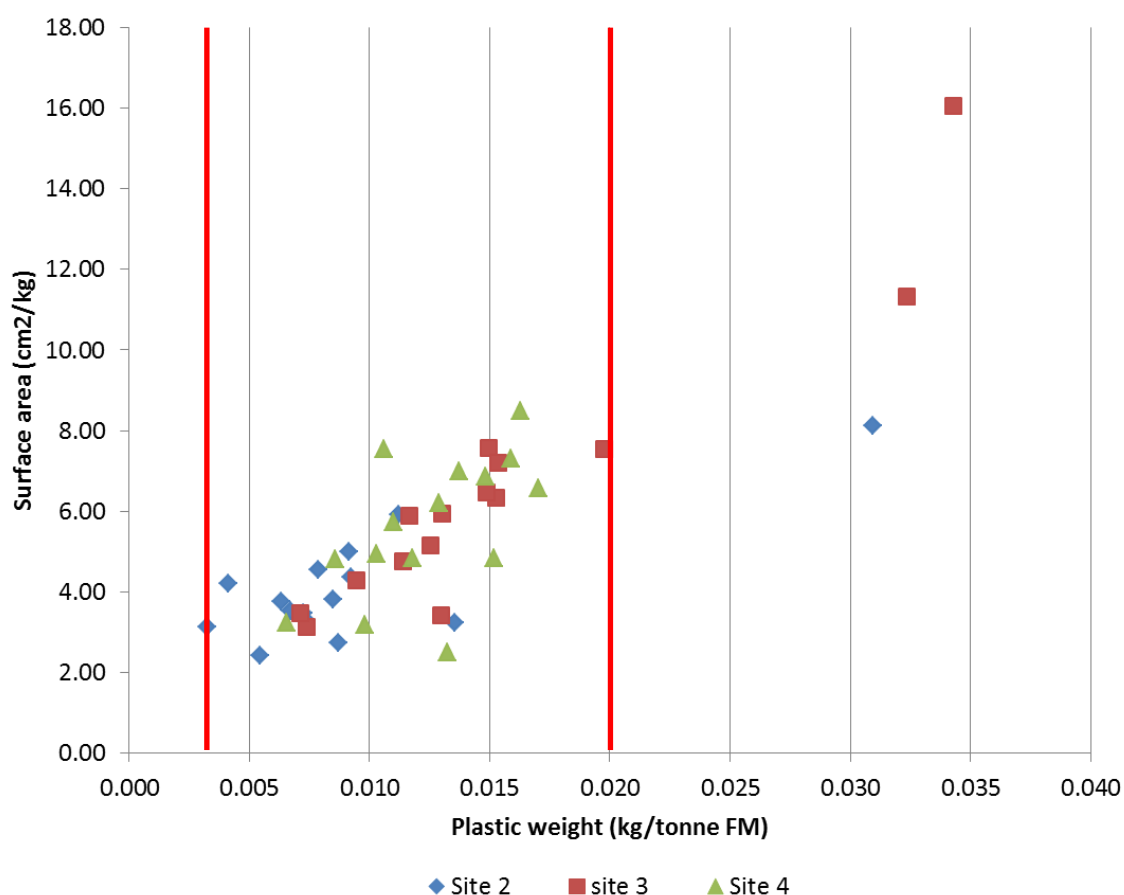


Figure 4. Correlation of individual digestate sample plastic contamination surface area to weight using data from sites 2-4. Taking into consideration total N content of digestates (Table 1), critical weight limits for April 2019 (to 3 dp) fall within the red vertical lines.

4.1.4 Plastic polymer type from digestate products

Polymer type was assessed for individual fragments recovered from sites 1-3 for three discrete samples each. Results of the analysis using FTIR-ATR are reported in % terms relative to the sum of plastic fragments in the three discrete samples per site (Figure 5). Fragments with less than 50 % match to the closest Hummel library polymer reference material were reported as ‘low % match’.

The figure shows there are clear differences in the main polymer types of fragments from different AD sites, although it should be kept in mind as with the previous data that these samples relate to a single sampling day for each site and as such further work will be required to determine if these results reflect actual trends for these sites.

In site 1, polyethylene/propylene 'blend' fragments were most common; however fragments falling in this category had matches which varied between 50-80 % of the closest library polymer reference material. Therefore, the abundance of fragments in this category should be viewed with caution and will require further analysis to fully elucidate the nature of these fragments.

The second most common polymer types in site 1 were polyethylene and polyvinyl chloride (PVC) with 23.5 and 23.3 % abundance respectively. Fragments in both of these categories had much stronger matches (typically 65-85 %) with the library reference materials than those placed in the polyethylene/propylene category. The abundance of PVC is noteworthy as this polymer type is often associated with phthalate plasticisers, which have been directly linked to having impacts on biological soil quality indicators (He et al., 2015). The presence/abundance of phthalates of the specific fragments was not determined, although further research is planned to investigate this.

Polypropylene was the third most abundant 'known' polymer type from site 1 (8.2%). In terms of confidence in identification of polymer type, these fragments had strong matches with the reference library at typically between 75-85 %.

The polyester category represented 7.6 % of fragments in site 1. Although, some matches were low (down to 51 %) this category was of interest as expected to include a mixture of relevant plastic types including group 1 polyethylene terephthalate (PET) depicted in Table 3 as well as other polyester polymers such as biodegradable PLA. In fact, analysis of a selection of fragments assigned to this category using the Hummel library achieved much higher matches (>90 %) against known virgin PLA spectra generated by us.

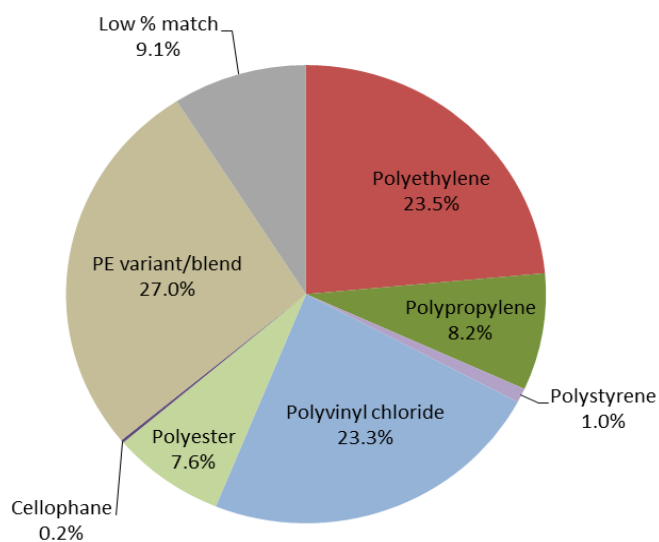
Polystyrene matches with the Hummel reference library were variable, ranging from 58-80 %; however, this included some rigid fragments which tended to produce lower matches because of assumed poor interfacing with the FTIR-ATR diamond. These rigid fragments could be pressed prior to FTIR-ATR analysis.

Finally, one fragment was categorised as cellophane, although with a match of only 54 % with the Hummel library polymer reference material further investigation would be required to confirm this.

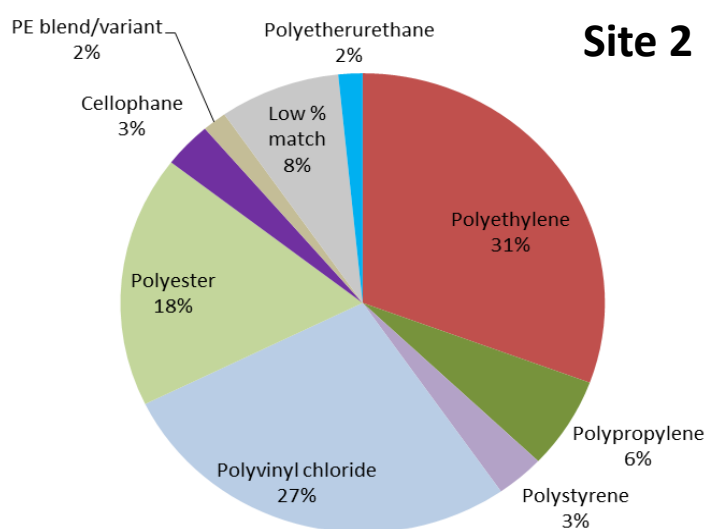
In site 2, polyethylene and PVC were the most common polymer types, closely followed by polyester. Together these polymer types accounted for 74 % of fragments. The remaining 26 % included small quantities of polypropylene, polystyrene, cellophane and polyethylene blends/variants. These polymer types had similar % matches to those found in site 1. One fragment had a good match (71 %) with polyetherurethane.

Site 3 polymer type abundance was clearly different from the other two sites, being dominated (63 %) by polyester fragments. PVC was the second most abundant 'known' polymer type for site 3, with strong matches with the reference library, as was also found in sites 1 and 2. Polyethylene and polypropylene had identical abundance in the site 3 sample. No polystyrene fragments were observed in the tested site 3 samples. Two site 3 fragments were 'identified' as cellophane and had slightly better matches (59 and 62 % respectively) with the reference library than those from sites 1 and 2. Finally, this site had the highest % of fragments with weak (<50 %) matches to the reference library. Therefore, again further work would be required to elucidate polymer type for these fragments.

Site 1



Site 2



Site 3

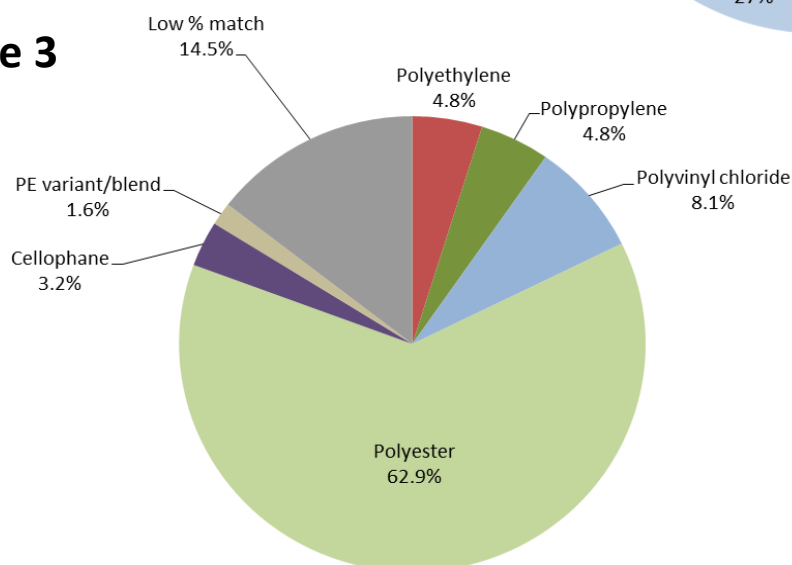


Figure 5: Pie charts showing abundance of different polymer types in fragment number terms analysed collectively from three discrete samples from sites 1-3. Note the polyester category covers a wide range of polymer types including PET (group 1) and biodegradable PLA.

4.1.5 Plastic fragments in soils

The collected agricultural soil samples were processed using the developed wet sieving approach with suspect plastic fragments recovered and weighed as reported (Table 10).

The results show that fragments ≥ 2 mm were recovered from permanent grassland with known digestate application (field 3) in three of the five samples at 0-5 cm depth only. No plastic fragments were recovered in grassland samples below 5 cm depth. The most obvious reason for the lack of fragments at depth is due to the fact that the field has not been cultivated during or prior to digestate application.

For the arable field with a history of digestate application (field 1), samples were expected to have received plastic fragments > 2 mm (based on previous analysis of specific digestate applied across this site), however, no fragments > 2 mm were recovered in any samples. This may be just due to the limited number of samples looked at. However, it could also be the result of differences in exposure and cultivation practices (and potentially other factors) affecting the fate of plastics in arable and grassland fields. For example, plastics in the grassland samples were held within a thick sward likely protecting the fragments from photodegradation and subsequent fragmentation. Further, in the arable field with digestate application, annual cultivation would likely have caused abrasion of fragments producing fragments < 2 mm.

Although fragments < 2 mm were not considered as part of this project, future risk based work should consider this especially given smaller fragments tend to have larger surface area for potential interaction with co-contaminants or leaching of additives.

Table 10: Weight of plastic fragments (> 2 mm) recovered from arable and grassland soils with and without digestate application. 'Zero' indicates no > 2 mm fragments recovered. For samples where plastic fragments were recovered, cells are shaded grey for ease of reference.

Field	Land use	Cultivation history ¹	Digestate application ¹	Sample location	Plastic contamination (g) ²		
					0-5 cm depth	5-15 cm depth	15-25 cm depth
1	Arable	Annual	Yes	1	Zero	Zero	Zero
1	Arable	Annual	Yes	2	Zero	Zero	Zero
1	Arable	Annual	Yes	3	Zero	Zero	Zero
1	Arable	Annual	Yes	4	Zero	Zero	Zero
1	Arable	Annual	Yes	5	Zero	Zero	Zero
2	Arable	Annual	No	1	Zero	Zero	Zero
2	Arable	Annual	No	2	Zero	Zero	Zero
2	Arable	Annual	No	3	Zero	Zero	Zero
2	Arable	Annual	No	4	Zero	Zero	Zero
2	Arable	Annual	No	5	Zero	Zero	Zero
3	Grassland	None	Yes	1	Zero	Zero ³	n/a
3	Grassland	None	Yes	2	0.0099	Zero	Zero
3	Grassland	None	Yes	3	Zero	Zero	Zero
3	Grassland	None	Yes	4	0.0023	Zero	Zero
3	Grassland	None	Yes	5	0.0034	Zero	Zero
4	Grassland	None	No	1	Zero	Zero	Zero

4	Grassland	None	No	2	Zero	Zero	Zero
4	Grassland	None	No	3	Zero	Zero	Zero
4	Grassland	None	No	4	Zero	Zero	Zero
4	Grassland	None	No	5	Zero	Zero	Zero

¹ Refer to table 6 for further detail on cultivation and digestate application history

² Soil sample size was ~200 cm³

³ Two samples from same depth due to obstruction

n/a – not applicable

For the three samples with plastic contamination, the eight individual fragments were further analysed for surface area, size and polymer type (Table 11).

The surface area data shows that five of the eight fragments were equal to or greater than the smallest mean fragment surface area of the four studied digestates (0.09 cm²). However, three fragments were smaller than this providing further support of the wet sieving approach in recovering >2 mm fragments generally. It should be noted though that these three fragments were either regular (square) in shape (fragment 5) or had colouration (fragments 6 and 7) which aided identification.

In terms of polymer type, only 3 of the 8 fragments gave >50 % matches to reference materials in the Hummel polymer library with two of these being rigid polystyrene fragments. The reason(s) for the low % matches are unknown at present but may include polymer degradation and associated limitations in the commercial polymer library used.

Table 11: Surface area, size and polymer type of plastic fragments (>2 mm) recovered grassland soils with digestate application (field 3).

Field location	Fragment no.	Surface area (cm ²)	Length (mm)	Width (mm)	Polymer type
2	1	0.59	12.0	9.0	Polypropylene
2	2	0.10	5.0	4.6	low % match (brittle)
2	3	0.09	4.3	3.6	low % match (brittle)
4	4	0.61	10.6	10.4	low % match
4	5	0.02	2.0	1.8	low % match
4	6	0.04	4.1	1.8	Polystyrene (rigid)
5	7	0.07	3.9	3.5	Polystyrene (rigid)
5	8	0.64	17.2	5.6	low % match

5.0 Conclusions and Future Work

Project conclusions are split into relevant sections with future work at the end of each section.

5.1.1 Amount of plastic in digestates

With the 'guidance on the management of food waste' report published by SEPA in December 2016, the work presented here was important in establishing the amount of plastic found in PAS110 digestates currently. Furthermore, this work set to provide insight into the likelihood of digestates being able to achieve future more stringent physical contamination limits.

The results show that three out of four sites are producing whole digestate (or separated liquor) which would likely pass April 2017 and April 2018 targets for plastic quantity (based on assumed or actual N content). One site achieved these limits by the careful selection of feedstocks alone, whereas, the other two used post-digestion screening. The much more stringent target for April 2019, however, may result in periodic or frequent failure for these sites with current practices in terms of feedstock quality acceptance, pre-digestion depackaging and post digestion screening. In order to evaluate the levels of plastic fragments in digestates against the proposed April 2019 limits, whilst maintaining distinctions in total N content, it was necessary to consider weight values to 3 rather than 2 dp. Modifications to make the PAS110 physical contaminant quantification method more 'robust' will enable SEPA to be more confident in the new limits. Such modifications will need to be incorporated into industry protocols and regulatory document revisions.

Two options are also proposed in section 5.1.3 to make physical contaminant testing more robust and differentiate samples based on relative abundance of film and rigid plastics.

FUTURE WORK

- Work with food waste producers, collection service providers, local councils and householders to continue to improve AD feedstock quality
- Work with food waste collectors and AD operators to help them better assess potential feedstock quality
- Work with AD operators to understand the long term performance and maintenance requirements of post-digestion screening equipment
- Generate a published industry protocol for weight based digestate physical contaminant analysis which includes reporting limit requirements.

5.1.2 Digestate plastic fragment surface area and size

The samples analysed during this project indicate that post digestion screening and/or careful selection of feedstocks reduces total and mean fragment surface area alongside weight of plastic. However, analysis of additional digestate samples from other sites with and without end screens would be necessary before any specific conclusions can be made on trends in fragments surface area or size.

In terms of plastic entering the soil following digestate application, the mean surface areas calculated here for site 2-4 translate to mean fragment sizes ranging from ~ 4 x 4 mm to ~ 3 x 3 mm. As many post-digestion plastic fragments are delicate it is expected that they will fragment after application to soil. At these sizes, fragments are difficult to detect and identify in the laboratory by naked eye (Echavarri-Bravo et al., 2017) let alone following land application, supporting the proposed limits from a visual perception perspective. However, where risk concerns extend beyond visual perception, fragments <2 mm will need to be considered both in digestates and soils.

FUTURE WORK

- Consider further viability and practicability of methods to isolate and analyse plastic fragments <2 mm from digestates and soils

5.1.3 Digestate plastic contamination analysis robustness and limits

The WRAP physical contaminant report (WRAP, 2016b) highlighted the limitation of weight based determination of plastic contamination in making distinction between samples with few rigid fragments and those with a high number of film fragments. Work here provides further data on how a surface area measure can support weight determination, particularly around critical limits planned for implementation in April 2019.

Analysis of digestate samples from a wider range of sites and on repeated occasion will generate a data set than can be used to set surface area limits which would come into play at the critical weight limits between 0.003 and 0.020 kg/tonne FM. Although the addition of a surface area measure would increase sample testing costs for AD operators, consultation with AD operators as part of the WRAP physical contaminants project suggested there was interest in such an approach (WRAP, 2016b).

An alternative approach to achieve the same aim would be to set separate limits for film plastic and other contaminants (the latter therefore including rigid plastic, metal, glass and paper fragments). This approach is used in parts of the USA and Germany where film only weight limits (0.1 % w/w) exist (Aspray, 2016). The approach should be more straightforward for the commercial laboratories to implement than the addition of a surface area measure and therefore likely have a slightly lesser impact of sample testing costs. Clear guidance would be needed to support the laboratories in distinguishing film from rigid plastics.

Wider stakeholder engagement is now possible with the WRAP physical contaminant report published. Updated cost estimates for the proposed modifications from the commercial laboratories would help this assessment process.

FUTURE WORK

- Stakeholder engagement is needed to determine whether the AD industry would be supportive of the addition of a surface area measure or separate film plastic weight limit to help provide greater assurance of digestate quality.

5.1.4 Polymer types in food waste derived digestate products

The results of the work clearly show that the makeup of polymer types does vary in digestate products from different sites depending on the feedstocks being processed. As many AD sites have changing feedstock supplies over time this will obviously have significant impact in the composition of polymer types in their digestate products.

FTIR-ATR was confirmed to be a useful screening tool for polymer type of plastic fragments recovered from the digestates at the 2 mm sieve cut off size. The Hummel reference library appeared better at determining some polymer types than others. For example, PE and PVC polymer fragments had consistently high matches with the reference library, whereas, others (e.g. polyester) gave varying results. Further work would be needed to distinguish different polyester types such as PET from PLA using a self-made reference library. Despite the above discussed limitation of the commercial reference library, there was strong evidence of both bio and petroplastics in digestates from all three sites. In the case of bioplastics specifically, there are indications of at least two types of bioplastic with matches to polyester and cellophane reference library matches. Several polyester fragments were subsequently analysed against virgin PLA film giving a much stronger match providing further support of this.

For fragments categorised as 'low % match' a mixture of known and unknown reasons include; the size of the fragment being too small to provide good contact with the ATR diamond, additives influence/interference in polymer determination, organic contamination, or the limitation of the standard library used.

Finally, although not part of the scope of this project, further analysis of PVC fragments could help assess whether phthalate additives are associated with these specific digestates. Phthalate additives have been banned in the European Union (EU) in children's toys; however, the status of phthalate use in food manufacture and packaging PVC is unconfirmed.

FUTURE WORK

- Development of bespoke reference library to include an increased number of relevant bioplastic polymer reference materials (work ongoing)
- Analysis of PVC fragments for phthalate additives

5.1.5 Plastic distribution in soil following digestate application

At the start of this project there were no published approaches for soil sampling for plastic contaminants specification or methods for the isolation of plastic fragments (>2 mm) from collected soil samples. As such this project appears to be the first public report to trial sampling and isolation approaches for determining the distribution of plastic in soil.

The results for the grassland surface (0-5 cm) samples provide strong support for the robustness of this basic sampling approach and wet sieving isolation method for fragments greater than 2 mm. As fragments were only found in three of the five samples, increased sample frequency (had resource been available) would have clearly provided a more robust assessment of plastic fragment distribution.

Given the same PAS 110 certified digestate was applied to the arable field; the lack of plastics isolated from the 0-5 cm depth samples would tend to suggest a difference in the fate of fragments in this system compared to permanent grassland. This would suggest methods to isolate fragments <2 mm are needed.

At this time it is not possible to conclude the appropriateness of the auger sample sizes used for samples from 5-25 cm depth. Certainly if greater resource had been available, a more involved sampling process to gather larger samples at these depths would have been used.

FUTURE WORK

- Use a higher frequency of soil sampling to give a more robust measure of plastic distribution and abundance at the field scale
- Develop methods for isolation of fragments <2 mm from soil (particularly those subjected to cultivation)

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