Programme Area: Bioenergy

Project: Characterisation of Feedstocks

Title: D6 Final Report (Phase 1)

Abstract:

The primary objective of this Project was to provide an understanding of UK produced biomass properties, how these vary and what causes this variability. This report provides an overview of the first phase (2015/16) of the Characterisation of Feedstocks project, excluding the extension work (reported in Deliverables D12 Report and D13 Whole Project Executive Report). The report starts with a summary of the key findings from the four studies carried out during 2015 and 2016. This is followed by an introduction to the context of the Project, including background, rationale and objectives; a description of the project approach, including the parameters investigated; the hypotheses tested; and the experimental protocols. The report then provides a summary of the two main areas of study, the results obtained and the statistical analyses used. An initial comparison of the results with those in the principal International database of biomass properties is discussed to put the results into context. The results and findings from the third and fourth areas of study are presented: comparison of variation within individual fields with those observed between sites, and the effect of pelletisation on Miscanthus properties. Commentary on the relative costs of establishment and production for the different feedstocks are provided. Finally the implications of, and recommendations to be drawn from the study are discussed.

Context:

The Characterisation of Feedstocks project provides an understanding of UK produced 2nd generation energy biomass properties, how these vary and what causes this variability. In this project, several types of UK-grown biomass, produced under varying conditions, were sampled. The biomass sampled included Miscanthus, Short Rotation Forestry (SRF) and Short Rotation Coppice (SRC) Willow. The samples were tested to an agreed schedule in an accredited laboratory. The results were analysed against the planting, growing, harvesting and storage conditions (i.e. the provenance) to understand what impacts different production and storage methods have on the biomass properties. The main outcome of this project is a better understanding of the key characteristics of UK biomass feedstocks (focusing on second generation) relevant in downstream energy conversion applications, and how these characteristics vary by provenance.

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Project Title:	**Characterisation of Biomass Feedstocks**
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Other participant:	**Uniper Technologies Ltd**
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Executive Summary

Within the UK, the installation of dedicated biomass power plants and the conversion of existing coal plants to use biomass, either in dedicated plants or co-fired with coal, has dramatically increased the demand for biomass feedstocks. At present home-grown output is significantly less than the demand, creating the opportunity for UK land-owners to supply this new market. Despite this, the level of understanding of biomass crops in the UK is still rather general. In particular, there is limited understanding of the variability in feedstock properties and a lack of recognition that differences in various properties can have a significant effect on the subsequent conversion to power and/or heat. Across all scales of use, feedstock quality is critically important in order to optimise plant performance, safeguard the environment, and maximise the financial benefits of the project.

The purpose of this deliverable is to inform the ETI on the variability in feedstock properties of UK produced energy biomass, the causes of these variations and the relationship between the feedstock properties and the provenance data collected.

Five feedstocks were included: *Miscanthus,* willow short rotation coppice (SRC), poplar SRC, poplar grown as short rotation forests (SRF), and spruce SRF, with poplar and Sitka spruce selected to represent broadleaved and coniferous biomass crops respectively. Provenance data include site properties (such as general climate zone and soil chemistry), the conditions at the time of sample collection, and past management of the site and crop with soil samples also collected for analysis. Feedstock samples were analysed in UKAS accredited laboratories for proximate and ultimate analyses (moisture, ash, volatile matter, net calorific value, gross calorific value, sulphur, chlorine, carbon, hydrogen, nitrogen); ash composition (SiO_2, Al_2O_3, Fe_2O_3, TiO_2, CaO, MgO, NaO, K_2O, Mn_3O_4, P_2O_5, BaO) plus trace metals (Ba, Be, Cr, Co, Cu, Mo, Ni, V, Zn, Hg, Pb, Cd, As, Se, Sb); halides (bromine and fluorine); and ash fusion temperature. Soil samples were analysed for the proportion of sand, silt, clay and organic matter; pH; cation exchange capacity; bio-available elements and total elements.

The following hypotheses about feedstock characteristics were postulated:

- feedstocks and plant parts within a feedstock will differ
- climate, soil type, harvesting time, storage and pelletisation (where relevant) will influence feedstock characteristics
- within a given field, feedstock properties will be relatively uniform.

Four related studies were carried out. The largest (Study 1) was designed to not only capture the magnitude of the variation in feedstock characteristics within commercial crops but also investigate the reasons behind this variation. The three smaller studies explored specific supplementary points. Study 2 investigated feedstock variability within individual sites (for *Miscanthus* and willow SRC only). Study 3 looked at the leaf properties of poplar and willow and compared them with whole plant harvested material. Finally Study 4 reviewed the impact of pelletisation on *Miscanthus* and woody feedstocks; this included quality information from Uniper's database of imported wood pellets.

The project generated a very large database, as presented in Deliverable D4. An extensive review of this database has been undertaken using a combination of statistical analysis, and the project team's knowledge of the analytical methods and downstream impacts of different chemical species. This allowed identification of relationships that were statistically, analytically and operationally significant for further evaluation.

Comparison of the different feedstocks in Studies 1 and 3 clearly shows that they varied in key fuel quality parameters that can have a significant impact on conversion technologies. Similarly, it was observed that there was variation in these parameters between plant parts. For example, the dry ash-free gross calorific value (GCV) was lowest for *Miscanthus* and in the woody biomass, increased in the order trunk wood< tops≈bark and was highest in the leaves. However, due to moisture and ash differences the net calorific value (NCV) on an as received basis was highest for *Miscanthus* with the different plant parts broadly equivalent for the woody biomass. Ash on a dry basis was low in the trunks, willow SRC and *Miscanthus* but was higher in the tops and bark and highest in the leaves. Levels of ash in the spruce SRF bark were lower than expected, potentially making this a better fuel than commonly believed, although this may be partially due to the harvesting method used for the project, which minimised contamination with soil, and the age of the bark. Sulphur and nitrogen concentrations were generally very low in the SRF trunks, increasing in the order; willow SRC ≈*Miscanthus*< tops≈bark and finally leaves. This order was similar for chlorine except that the concentrations in *Miscanthus* were elevated and similar to those of leaves. Certain trace elements showed some intriguing differences between feedstocks and plant parts, though for most concentrations were low - often at or below the limit of detection - and broadly similar across all feedstocks and plant parts. The ash composition was most noticeably different in *Miscanthus* where silica dominated whereas ash of the other feedstocks was dominated by calcium compounds.

Structured analyses were undertaken using four factors (climate zone, generic soil type, harvest time and storage impacts) and combinations thereof. In most cases, soil type was not a key determinant of feedstock characteristics; this is thought to be because the sites had average or below average levels of metals/metalloids. In contrast harvesting time (which was tested for SRF crops only) and storage had a marked effect. Climate zone was generally not influential for SRF crops, but was more frequently significant for *Miscanthus.* The data allowed statistical analysis of only limited crop management practices, but this identified possible relationships between year of planting and both cadmium in *Miscanthus* and sodium in willow SRC. The age of sampled material appeared to influence several characteristics in both willow SRC and spruce SRF bark, whilst planting density had impacts on levels of barium in spruce SRF wood as well as the volatile matter, nitrogen, copper and cadmium in spruce SRF tops.

A qualitative ranking of factors affecting the important characteristics extracted from the analysis of the individual feedstocks indicates that feedstock characteristics were not affected in a consistent way by the site properties and crop management. Nevertheless, the following general suggestions can be made. The implications for growers of *Miscanthus*, poplar SRF and spruce SRF are that the most important factor affecting moisture and NCV, i.e. storage, can be manipulated. In the case of *Miscanthus*, some of the chemical properties might be modified by the selection of field, whereas most of the key macronutrients are primarily dependent on the climate zone. Willow SRC growers seem to have a reasonable degree of control over some of the important feedstock characteristics by their choice of harvesting time (as a means of controlling leaf content). For poplar SRF and spruce SRF, besides moisture

content and NCV which are mentioned above, many of the other properties can be adjusted by the choice of the plant part to market and harvest time. Feedstock properties were relatively insensitive to the way spruce SRF was grown. For all feedstocks, the implications for buyers are that consideration must be given to the feedstock characteristics of prime importance in a particular application.

For the in-field variation studies (Study 2), the project investigated feedstock variability within and between sites for *Miscanthus* and willow SRC. For some feedstock characteristics, the variation between the sites was greater than that seen within samples taken from across the same field, whilst for others the variation within-field was much greater than that between different sites. Similar behaviour between the two feedstocks was seen for a number of individual fuel quality parameters.

For Study 4, a commercial supplier provided raw and pelletised *Miscanthus* samples for comparison. However, it was found that these varied considerably in a number of key parameters; in particular the first two batches of pellets received were contaminated with caustic soda, which is used as an additive to improve pelletisation performance. The elevated sodium levels this caused would have severe consequences for conversion plans in terms of corrosion and fouling. This illustrates that common commercial practice can have significant impact on fuel quality. There was also a tendency for higher levels of some metals in the pellets compared to the raw material, possibly indicating contamination due to the pelletisation process.

Large datasets for biomass composition are rare; one of the largest is the Phyllis2 database maintained by ECN in the Netherlands but even here the number of samples of some feedstocks are very low, particularly for the more specialised analysis. A comparison of the feedstock characteristics collected within the project with this database indicated generally good agreement for *Miscanthus* and only minor differences for willow SRC with the exception of manganese which was much higher in the project samples. Comparison of the data for poplar and spruce was less reliable as the Phyllis2 does not generally distinguish between different plant fractions, apart from spruce SRF bark.

Data provided on internationally traded wood pellets by Uniper highlighted an extremely consistent and homogeneous fuel and were tightly clustered compared to the raw feedstocks analysed in this project. A number of quality standards exist for wood pellet depending on the market application and these have recently been defined in ISO17225-2:2014. Depending on which pellet class limits are applied, some of the feedstocks from Study 1 would not meet the dry nitrogen and chlorine content, whilst for dry ash, the spruce SRF trunk was the only plant part to consistently meet the strictest limit. In terms of trace elements, the limit for cadmium was the most challenging and was exceeded by a proportion of the poplar SRF dataset (both trunk and tops) and some willow samples, although it is comfortably achieved for all the spruce SRF plant parts. In addition, a few poplar SRF tops and willow stem samples exceeded some of the limits for copper and zinc. None of the other trace element limits proved to be an issue.

Costs of feedstock types were in most cases provided by the feedstock management companies and verified by growers. In general terms, the largest differences between the feedstock types was in the initial establishment and management costs with spruce SRF and poplar SRF incurring higher costs in the early years. Willow SRC costs were typically higher than *Miscanthus*, largely due to the additional cut back operations at the end of year one, but the difference in costs across all feedstocks was marginal. Taking account of ground preparation, planting, the purchase of planting stock and cut back where relevant, the total

establishment costs ranged from £1000 to £1,500/ha for all feedstocks. Harvesting costs were the largest management cost and were noticeably different between feedstocks, with the poplar and spruce SRF incurring the highest costs on a per oven dried tonne basis.

Reviewing the project as a whole, the sites were very 'clean', with below average or very low levels of soil metals and metalloids, which probably explains the absence of any impact of soil type and the very small number of strong correlations found between feedstock ash characteristics and soil properties. This raises an unanswered question of what would the feedstock uptake be in contaminated sites, or from feedstocks/sites which have been regularly treated with sewage sludge or other organic waste products. Willow SRC leaves tended to have the strongest correlation between feedstock ash characteristics and the soil composition; this could be due to the fact that several of their soils had considerably higher heavy metal content than the other sites, being at or just above the UK average.

Climate zone had little influence on overall feedstock characteristics, except on moisture and its related attributes within a feedstock; other characteristics were not significantly different across the different climate zones.

All feedstock types, with the exception of the willow SRC, reduced in moisture content from point of harvesting to sampling at the end of the storage period. The impact of storage was more marked for SRF which was stored for three months than for *Miscanthus* and willow SRC, which were stored for ca. one month, where storage was of very little operational significance to all the feedstock characteristics apart from moisture and linked attributes. The willow SRC only experienced a one-month period of external storage time, where the moisture content did not noticeably change, indicating that a longer time frame is required to reduce willow SRC chip/billets. Although *Miscanthus* did dry with one month of storage as bales, there was a much larger reduction in moisture between the initial cutting/harvest timing and the collection/baling operation, typically of 2 weeks' duration.

Where harvesting time was investigated, (poplar and spruce SRF) there was often an important impact on feedstock properties, especially of the tops. In several instances the exact effect depended on the climate zone.

The elevated levels of critical fuel components in some of the feedstocks may limit their use as single feedstocks in some conversion technologies. However, opportunities for blending or other pre-treatment options to improve the quality and consistency may exist, and appropriate tools and methods should be developed to support this option.

Key Findings

- The sampling procedures were robust and consistent giving a high degree of confidence in the dataset.
- Chemical properties of feedstocks differed in ways that have the potential to affect the downstream conversion.
- The Gross Calorific Value was lowest for the *Miscanthus*, the willow SRC and trunks of the other feedstocks, increasing in the tops and was highest in the leaves and bark.

- *Miscanthus* had the lowest and most variable moisture content as harvested; the trunk wood and tops contained typically 50-60% moisture with the leaves containing >60% moisture.
- The Net Calorific Value (NCV) of *Miscanthus* was generally highest but was also very variable. For the woody biomass, the NCV was broadly similar for the stems and tops but the NCV of leaves tended to be lower than for the woodier parts of the plant.
- Ash levels and N in the stems of the woody biomass were very low, increasing in the tops, with the leaves containing the highest levels; spruce SRF bark levels were comparable with those in the spruce SRF tops; *Miscanthus* levels were comparable with those in the tops of the woody biomass types.
- Sulphur was much higher in leaves than the other plant parts.
- Chlorine levels were highest in *Miscanthus* and were very variable. The willow SRC leaves contained markedly higher levels of chlorine than leaves from the poplar SRF. The trunks generally contained chlorine levels that were lower than the limit of analytical detection of 0.01%.
- Trace and minor elements - within the woody feedstock types, the trunks contained the lowest levels followed by increasing concentrations in the tops and finally the leaves. For the majority of elements, the bark of spruce SRF contained similar concentrations to the tops.
- Leaves showed particularly high levels of zinc, which is a potential corrosion concern, and cadmium which is of environmental concern.
- Ash composition - with the exception of the *Miscanthus*, all of the feedstock ashes were predominantly composed of calcium carbonate, with potassium oxide levels also high. By contrast, the *Miscanthus* samples contained significant levels of silica in their ash.
- On the basis of alkali index, *Miscanthus* was comparable to tops of woody plants though poorer than woody stems. The high alkali index of willow and poplar leaves suggested potential for slagging and fouling.
- Harvesting time had a marked effect, though this was tested for SRF crops only.
- Storage had a marked effect, particularly the longer (3 month) durations; while this was mainly associated with moisture changes, changes to the composition of the second harvest poplar SRFduring storage were probably associated with leaf loss.
- Soil type was not a key determinant of feedstock characteristics; this is thought to be because the sites had average or below average levels of metals/metalloids.
- Climate zone was generally not influential for SRF crops, but was more significant for *Miscanthus*.
- Plant part had a dominant impact within willow SRC, poplar SRF and spruce SRF biomass.
- For the in-field variation studies, whether more variation was seen within each site or between sites depended on the parameter. Both *Miscanthus* and willow SRC gave similar patterns for which elements were more variable within a field and which were more variable between fields.

- Pelletisation of *Miscanthus*: the major change associated with pelletisation of *Miscanthus* was an increase in bulk density; the dry ash content was generally higher after pelletisation. The results indicated that there was a relatively high risk of product contamination, either from deliberate use of additives, from other materials or wear products from grinding process or the pellet mill itself.
- Of the ETI samples, only the spruce SRF stem wood met the strictest criteria for relevant standards of industrial pellets.

Contents

1 Introduction

1.1 Background and context to the project

At a global scale, the use of biomass as a source of energy has transformed in the last two decades, from widespread utilisation within a local geographic area for cooking and heating, to use for power generation at a large scale and combined heat and power generation at a medium scale. This change is largely in response to policy and financial drivers to limit CO_2 emissions from fossil fuels, with biomass combustion generally considered to be CO_2 neutral (although account must be taken of the sustainability of the supply and upstream emissions from production and transport). As a result of the biomass tonnages required for large-scale industrial operations, global trading of biomass feedstocks is now well established. The more traditional use for heat persists and has even grown in some developed countries, due to a variety of reasons, including environmental, financial and aesthetic.

Across all scales of use, feedstock quality is critically important in order to optimise plant performance, safeguard the environment, and maximise the financial returns of the project.

Within the UK, the installation of dedicated biomass power plants and the conversion of existing coal plants to use biomass (either as the primary fuel or co-fired with coal), has dramatically increased the demand for biomass feedstocks. At present, home-grown output is significantly less than the demand, creating the opportunity for UK land-owners to expand to supply this new market. Despite this, the level of understanding of biomass crops in the UK is still rather general; in particular there is limited understanding of the variability in feedstock properties and a lack of recognition that differences in various properties can have a very significant effect on the subsequent conversion to power and/or heat. The overall purpose of this project is to address these knowledge gaps.

At present the use of dedicated energy crops in the UK is relatively modest in comparison to other forms of biomass such as products of conventional forestry, agricultural residues and wastes. DUKES 2015 quotes an estimate from Defra, based on Renewables Obligation Sustainability reporting, that 47,000 tonnes of UK *Miscanthus* and 9,000 tonnes of UK SRC were burned for energy. Drax power station is the biggest user, and in 2014 burned 25,000 tonnes of *Miscanthus* and 6,000 tonnes of willow SRC, all from the UK. This, however is in contrast to a total of 4 million tonnes of biomass, of which 2.4 million tonnes were imported from USA and 0.9 million tonnes from Canada, almost all in the form of wood pellets. In the Ofgem Biomass Sustainability Report 2013-14 dataset, the total consumption of solid biomass fuel was 5.7 million tonnes.

1.2 Objectives

The particular purpose of this deliverable is to inform the ETI on the variability in feedstock properties of UK produced energy biomass types, the causes of these variations and the relationship between the feedstock properties and the provenance data collected. Five feedstocks were included: *Miscanthus,* willow short rotation coppice (SRC), poplar SRC, poplar grown as short rotation forests (SRF), and spruce SRF, where poplar and Sitka spruce were selected as representative of potential broadleaved and coniferous biomass crops respectively. Provenance data include site properties (such as general climate zone and soil chemistry), the conditions at the time of sample collection, and past management of the site and crop. Subsequently, the outcomes will be used by the ETI in combination with the two

partner projects (Techno-Economic Assessment of Biomass Pre-processing Technologies and Refining Estimates of Land for Biomass) to understand options for future ETI demonstration activities and investments.

This deliverable (D6) is preceded by D1, which provided a detailed schedule of work, and D2, which described the methodologies used to both collect representative feedstock samples and analyse these samples for properties relevant to their later conversion. D3 was an intermediate database showing results and provenance data collected for fresh feedstock which was updated in D4 to include the equivalent analyses of feedstock characteristics after storage plus data on pellets of *Miscanthus* and routine samples of commercial wood pellets imported by Uniper. In D5 the information on all the fresh samples was described, analysed and reported, while D6 additionally includes stored biomass, as well as leaves and pellets, and evaluates all of the data in more detail. In addition, D6 places greater emphasis on the variability within and between feedstocks, compares all the feedstock results obtained in the course of this contract with available information from external sources, collates available information on the costs of establishment of the five feedstocks and interprets the feedstock characteristics in terms of the implications for downstream conversion.

For ease of reference, the Deliverable Description and Acceptance Criteria in the Technology Contract are given in Appendix 1. The specific objectives of D6 stated in the contract are to:

- Identify the uncertainty ranges for a representative range of UK produced (fresh) energy crop qualities (*Miscanthus,* willow SRC, poplar SRC, poplar SRF, and spruce SRF).
- Relate the fresh energy crop quality variations obtained back to provenance data (including site management history) collected. The relationships discussed shall link geographical data (e.g. soil type, climate), management actions and practices to biomass properties and their variations.
- Identify farm gate feedstock prices and production costs (where possible) for use by the techno-economic assessment of biomass pre-treatment technologies project.

1.3 Hypotheses

Guided by the background given in the Request for Proposal, the following hypotheses were set out and addressed in the contract:

1. The feedstocks examined range from *Miscanthus*, through woody deciduous plants grown for only a few years and regenerated by coppicing (willow and poplar), to small deciduous and evergreen trees (poplar and Sitka spruce respectively). It is therefore hypothesised that the feedstocks will differ in their fuel properties and/or composition.
2. With the exception of the *Miscanthus,* the feedstocks are differentiated into plant parts that have different functions, e.g. mechanical support versus photosynthesis; therefore we hypothesise that these plant parts will differ in their fuel properties and/or composition.
3. Feedstock properties will differ depending on the climate the crop is exposed to.
4. Feedstock properties will differ depending on the soil composition and characteristics of the site.
5. Feedstock properties will differ according to the time of year that the biomass is harvested.

6. Feedstock properties will differ with storage.
7. Within a given field, feedstock properties will be relatively uniform.
8. The process of pelletisation will influence the fuel properties and/or composition.

2 Methodology

2.1 Sampling and analysis

The aims of the field sampling and laboratory analyses were to maximise consistency and repeatability and minimise contamination, such that the variability of the data was a true reflection of the variability of the feedstock.

Sampling of both soil and feedstocks has been previously described in D2 (Appendices 5 to 12); flow charts in D2 (Appendix 13) described the process for sample collection and dispatch. Standard operating procedures (SOPs) for sampling were developed and are presented in Table 3 of D2. Fuel analysis was primarily undertaken in the ISO17025-accredited internal laboratories of Uniper Technologies, following standard procedures as listed in Table 2 of D2, although ash fusion temperatures were sub-contracted to UKAS accredited laboratories, as were soil analyses. Flow charts in D2 Appendix 14 described the laboratory process for sample preparation and testing.

2.2 Feedstocks

Five feedstocks were included in the study: *Miscanthus,* willow short rotation coppice (SRC), poplar SRC, poplar grown as short rotation forests (SRF), and Sitka spruce SRF. All were commercial crops which had received normal commercial management. In this way we could address hypothesis 1.

2.3 Plant fractions

The plant parts sampled and analysed were chosen to represent commercial practice, therefore all of the above-ground biomass (using typical harvest heights) has been analysed for *Miscanthus* and SRC. This is also likely to be a common practice for SRF, but it is also a realistic possibility that only the upper stem and associated branch and leaf material are sold for bio-energy with the lower larger stem material being sold to alterative markets, e.g. construction or fencing. Moreover, it is a commercial possibility that the bark of conifers is separated from the stem wood and sold for mulch; in general the bark of broadleaved species is too thin for its removal for alternative uses to be a viable commercial option.

Consequently in the case of *Miscanthus*, willow SRC and poplar SRC the results are for the above ground material as a whole. Willow and poplar leaves were collected separately on a subset of samples to provide some understanding of the impact of harvesting outside of the typical dormant period when few, if any, leaves would be present. For poplar SRF, the above ground material was split into two fractions: (a) the trunk (taken from the cutting point at the base to a point where the diameter has reduced to 7 cm) and (b) the tops (the upper part of the stem with a diameter less than 7 cm plus the associated branches and leaves). For spruce SRF, the above ground material was split into trunk and tops as for the poplar (with branches and needles included in the tops section), but the spruce trunk was debarked to form a third fraction. By separating out the plant fractions we were able to address hypothesis 2.

2.4 Sampling approach

The backbone of the project was the field sampling of representative commercial crops followed by laboratory analysis of their fuel properties and composition. Prior to the field sampling, Forest Research's Geographic Information System (GIS) software was used to split Britain into average climate zones and predicted soil types. The databases upon which the

soil designations were based were from the National Soil Map of Scotland from the James Hutton Institute, and the National Soil Map of England and Wales from The National Soil Resources Institute, converted by the Forestry Commission to the FC classification system at 1:250,000 resolution, although for the existing forestry sites, more detailed 1:10,000 Forestry Commission soils maps were used. The approach was then to identify three sampling locations within each of the most appropriate combinations of average climate zone and predicted soil type for each feedstock. This replication within a climate zone and soil type was designed to allow a structured analysis of the impact of these variables on feedstock characteristics. This sampling approach was designed to allow us to address hypotheses 3 and 4.

Due to harvest timing, it was not possible to visit the proposed sampling sites in advance to collect and analyse the soils and confirm the GIS categorisation. For the final evaluation of the data collected, the structured analysis of factors was modified to use the soil types determined at each site instead of the predicted soil types, since the analysed soil types were in many cases markedly different from those predicted. In particular, all of the locations identified by GIS as having heavy soils were found to have lighter soils after analysis, with the result that no material grown on heavy soil was sampled. For future studies of this type it is recommended that soil data is collected prior to harvest to better inform site selection.

Hypotheses 5 and 6 were addressed within the same sampling framework by sampling from the same sites at two separate times and storing the sampled material for durations that were operationally realistic. Due to the timing of the project start, only one commercially-relevant harvest of *Miscanthus* and willow SRC could be taken, but two realistic harvest times were possible for both the poplar and spruce SRF.

All sampling, handling and lab analyses followed a set of protocols designed to maximise consistency and at the same time minimise contamination (more detail is given in D1 and D2). While this was the correct approach to meet the project's objectives, for commercial operations there is a higher risk of contamination due to the harvesting and processing practices used (e.g. soil, rocks); this is discussed in Section 12.

Commercial practice is to plant poplar and willow SRC as a mixture of different varieties to counteract pest and disease attacks. In order to minimise variability due to varietal differences within poplar SRF, four trees of each of three varieties (Gaver, Ghoy and Gibecq) were sampled at each site in both Study 1 and 3. For willow SRC it was more difficult to identify varieties in their leaf-off condition, so identical varieties could not be sampled across all sites therefore representative samples of the harvested crop from the selected fields were collected regardless of the varieties being grown. The impact of different varieties are being investigated further in Phase 2 of the project.

2.5 Study overview

Four related but different studies are reported, with an overview of the primary variables examined in each study shown in Table 2-1. The largest (Study 1) was designed to investigate the reasons behind any observed variation in feedstock characteristics. Samples were taken from a variety of climate zones and soil types. The original study design presented in D1 included sample collection from three different locations in each combination of climate zone and soil type. However, in practice this was not always achieved for reasons including insufficient sites available for some combinations and the mismatch between predicted and actual soil types discussed in Section 2.4. At each location, biomass and soil samples were

collected from multiple points within the site, then bulked and subsampled for lab analysis. Site conditions at the time of field sampling were noted as well as information on the crop and its past management (see Appendix 2).

The three smaller studies explored specific supplementary points:

- Study 2 investigated feedstock variability within a site (*Miscanthus* and one variety of willow SRC only) addressing hypothesis 7. Whilst Study 1 provided an overall average for each site and should be typical of the harvested crop, there could be situations where only parts of site are harvested at any one time. There is therefore a practical value in understanding the differences found across individual sites.
- Study 3 investigated leaf properties (poplar SRF and willow SRC) for comparison to the feedstocks containing little or no leaf material (as obtained in Study 1). This addresses in part hypothesis 2. While it would be usual practice to harvest without leaves, there could be situations when crops are harvested when leaves are present. In view of the expected chemical differences between leaves and other plant parts, there is practical value in describing the leaf composition to understand the impact of including leaf material on the general feedstock properties.
- Study 4 investigated pellet properties. The process of pelletising may alter the composition compared to the raw feedstock, which was formalised as hypothesis 8. Furthermore, significant quantities of biomass are imported in pellet form, especially wood pellets, and Uniper have contributed data from the routine sampling of imported wood pellets which allows comparison with the characteristics of the woody biomass sampled within the project.

Table 2-1: Overview of sampling undertaken in the four studies

Feedstock	Climatic zone	Soil types	Harvest Time	Plant part	Time of Sample
Study 1: Variability and its determinants					
Miscanthus	Warm/dry Warm/moist	Light Medium	February to April	whole	at harvest in-field prior to baling 1 month stored as bales
Willow SRC	Warm/dry Warm/moist	Light Medium	February to May	whole	at harvest 1 month stored as chips
Poplar SRC	Warm/dry	Light Medium	June	whole	at harvest
Poplar SRF	Warm/dry Warm/moist	Light Medium	April July/August	trunk tops	at harvest 3 months stored
Spruce SRF	Warm/moist Cold/wet	Light mineral Light organic Light peat	March June	trunk tops	at harvest 3 months stored
				bark	at harvest
Study 2: Within-field variation					
Miscanthus	Warm/dry	Light	March/April	whole	at harvest
Willow SRC	Warm/dry	Light Medium	March	whole	at harvest
Study 3: Leaves					
Poplar SRF	Warm/dry Warm/moist	Light Medium	July/August	leaves only	In full leaf
Willow SRC	Warm/dry	Light Medium	September	leaves only	In full leaf
Study 4: Pelleting					
Miscanthus	n/a	n/a	n/a	whole	before and after pelleting

2.6 Statistical approach and analysis

2.6.1 Overview

The project has generated a very large database (presented in D4). The data has have been interpreted using statistical analysis in combination with the project team's understanding of the energy and heat sector and conversion technologies to focus on those parameters which are most influential. Flow charts describing the steps used to focus on the results to analyse and then illustrate in the main project report are shown below. Figure 2-1a and b describe the steps for the feedstock characteristics and provenance information respectively in Study 1 while Figure 2-1c describes the steps from Study 2. The statistical approaches are described in Sections 2.6.3 and 2.6.4, while the project team's approach to the selection of key parameters is described in Section 3. In order to keep the main report concise, the supporting analyses have been put in the appendices, and only summaries or highly relevant small tables incorporated into the text.

2.6.2 Quality assurance of data

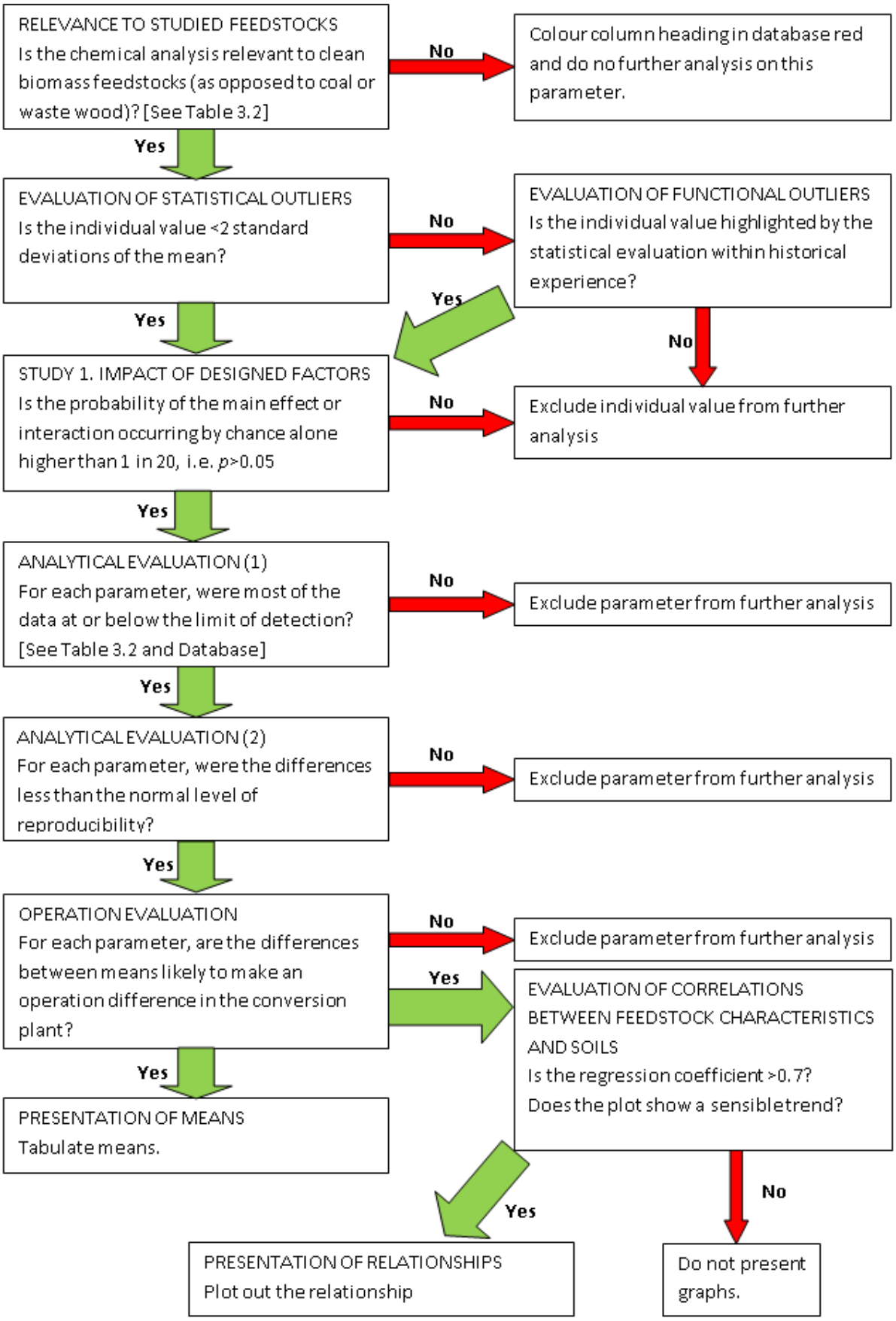
There were several layers of data review, ending with a very objective systematic assessment of all outliers.

For majority of the chemical analyses the analysis was undertaken once. However, for carbon, hydrogen, and nitrogen, each value is an average of two replicates. Data were reviewed as each set of analysis was added to the master file and in a small number of cases samples were reanalysed.

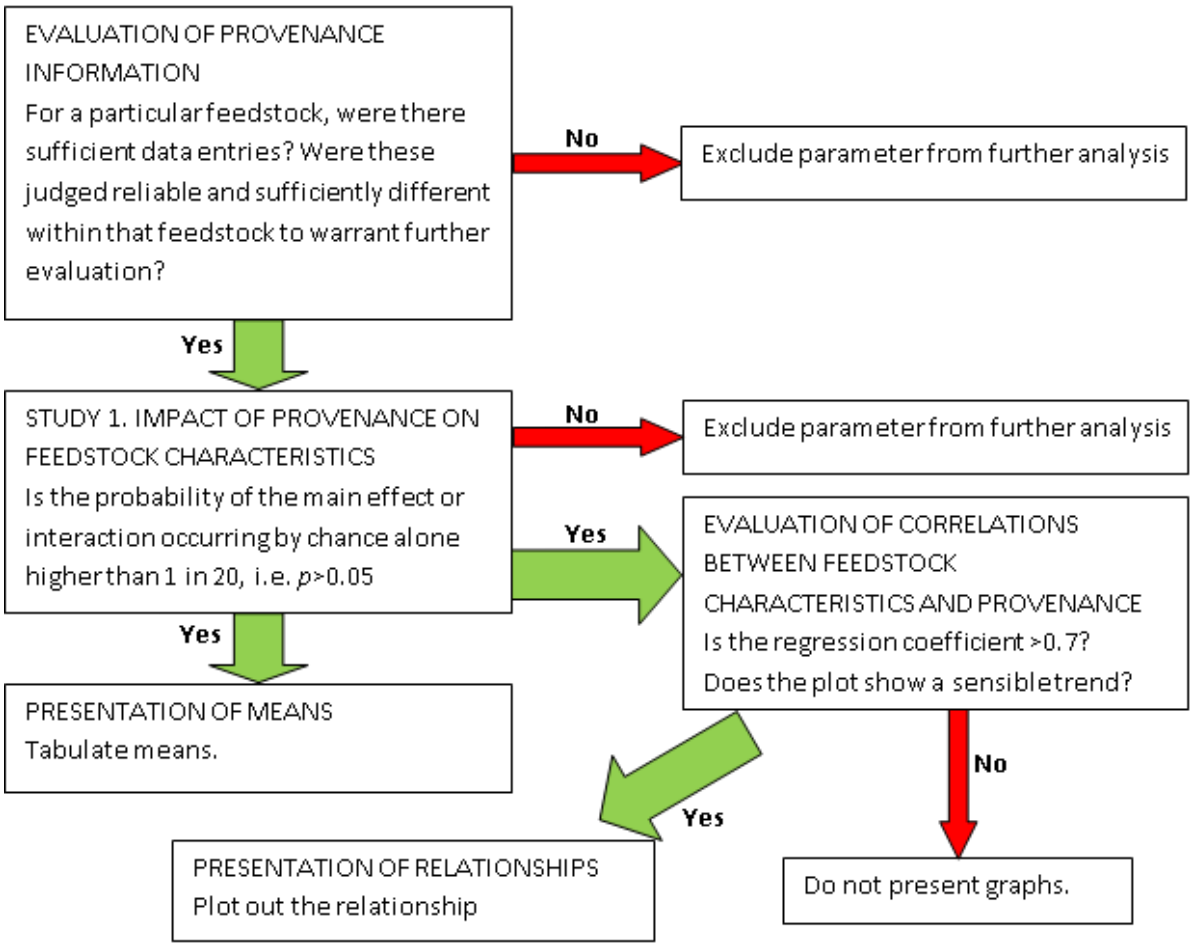
Finally, all feedstock characteristics were reviewed objectively to flag outliers using GenStat to list all points that lay beyond two standard deviations of the mean. Outlier review was done separately for the trunks, tops and bark of the spruce SRF and the trunks and tops of poplar SRF. The lists of statistical outliers were then scrutinised and any that showed a systematic difference from the norm – suggesting that the sample was contaminated in some way – or were markedly different from the project team's experience were marked to be excluded from further analysis by GenStat. Many of the values identified as statistical outliers were retained as they were considered to be within the normal variation of the biomass feedstock. These are indicated by green shaded cells within the D4 database; those flagged values which were deemed to be "true" outliers are shaded red in D4 and are also discussed in Appendix 3.

Figure 2-1

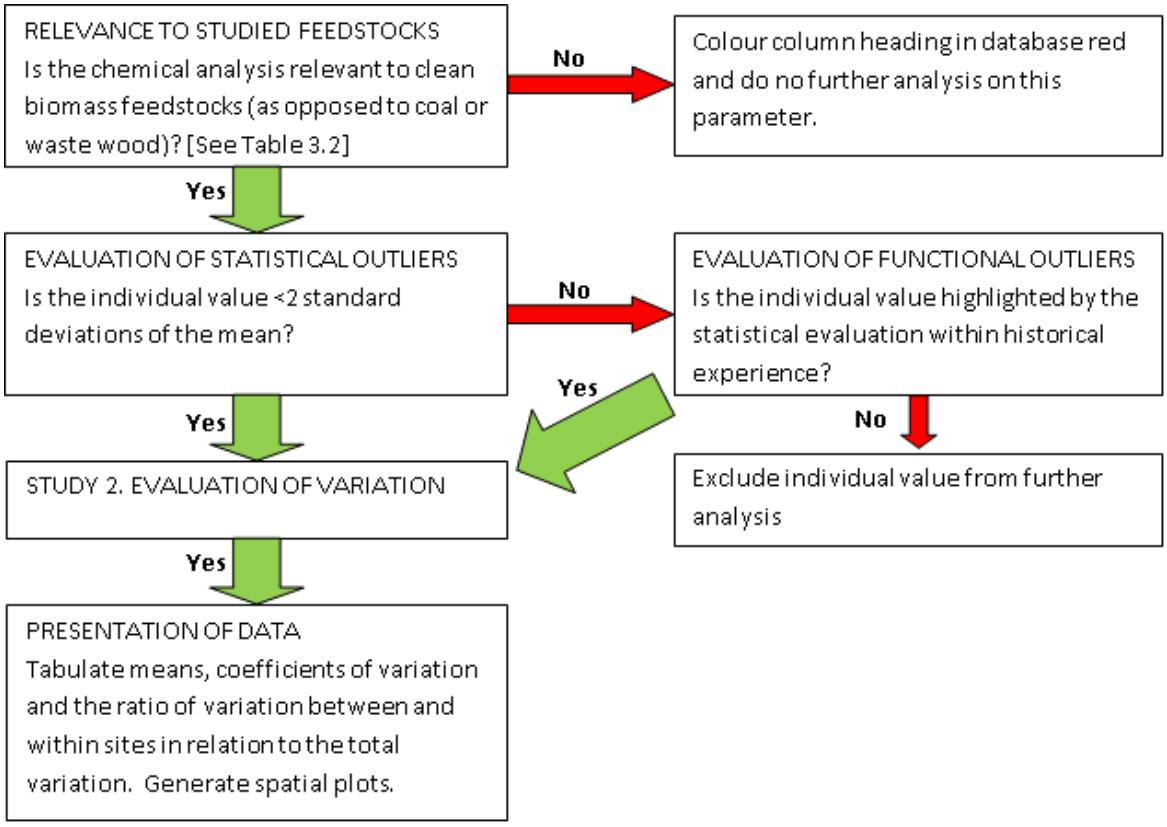
a)


RELEVANCE TO STUDIED FEEDSTOCKS
Is the chemical analysis relevant to clean biomass feedstocks (as opposed to coal or waste wood)? [See Table 3.2]
No
Colour column heading in database red and do no further analysis on this parameter.
Yes
EVALUATION OF STATISTICAL OUTLIERS
Is the individual value <2 standard deviations of the mean?
No
EVALUATION OF FUNCTIONAL OUTLIERS
Is the individual value highlighted by the statistical evaluation within historical experience?
Yes
Yes
No
STUDY 1. IMPACT OF DESIGNED FACTORS
Is the probability of the main effect or interaction occurring by chance alone higher than 1 in 20, i.e. p>0.05
No
Exclude individual value from further analysis
Yes
ANALYTICAL EVALUATION (1)
For each parameter, were most of the data at or below the limit of detection? [See Table 3.2 and Database]
No
Exclude parameter from further analysis
Yes
ANALYTICAL EVALUATION (2)
For each parameter, were the differences less than the normal level of reproducibility?
No
Exclude parameter from further analysis
Yes
OPERATION EVALUATION
For each parameter, are the differences between means likely to make an operation difference in the conversion plant?
No
Exclude parameter from further analysis
Yes
EVALUATION OF CORRELATIONS BETWEEN FEEDSTOCK CHARACTERISTICS AND SOILS
Is the regression coefficient >0.7?
Does the plot show a sensible trend?
Yes
No
PRESENTATION OF MEANS
Tabulate means.
PRESENTATION OF RELATIONSHIPS
Plot out the relationship
Do not present graphs.

b)


EVALUATION OF PROVENANCE INFORMATION
For a particular feedstock, were there sufficient data entries? Were these judged reliable and sufficiently different within that feedstock to warrant further evaluation?
No
Exclude parameter from further analysis
Yes
STUDY 1. IMPACT OF PROVENANCE ON FEEDSTOCK CHARACTERISTICS
Is the probability of the main effect or interaction occurring by chance alone higher than 1 in 20, i.e. p>0.05
No
Exclude parameter from further analysis
Yes
EVALUATION OF CORRELATIONS BETWEEN FEEDSTOCK CHARACTERISTICS AND PROVENANCE
Is the regression coefficient >0.7?
Does the plot show a sensible trend?
Yes
PRESENTATION OF MEANS
Tabulate means.
Yes
PRESENTATION OF RELATIONSHIPS
Plot out the relationship
No
Do not present graphs.

c)


RELEVANCE TO STUDIED FEEDSTOCKS
Is the chemical analysis relevant to clean biomass feedstocks (as opposed to coal or waste wood)? [See Table 3.2]
No
Colour column heading in database red and do no further analysis on this parameter.
Yes
EVALUATION OF STATISTICAL OUTLIERS
Is the individual value <2 standard deviations of the mean?
No
EVALUATION OF FUNCTIONAL OUTLIERS
Is the individual value highlighted by the statistical evaluation within historical experience?
Yes
Yes
No
STUDY 2. EVALUATION OF VARIATION
Exclude individual value from further analysis
Yes
PRESENTATION OF DATA
Tabulate means, coefficients of variation and the ratio of variation between and within sites in relation to the total variation. Generate spatial plots.

2.6.3 Statistical analysis

All statistical analyses were done using GenStat 16, which is a powerful statistical language, particularly useful for the analysis of structured experimental factors (see Section 2.6.4).

The statistical tests used in the intermediate investigation of Study 1 and 2 data were described briefly in D5. Here we expand on these to cover the greater range of tests needed to investigate all eight of the hypotheses in Studies 1 to 4, as set out in Section 1.3.

For Studies 1 & 3, structured contrasts of for example climate zone, soil type, harvesting time and storage, were investigated using two slightly different algorithms. ANOVA (Analysis of Variance) was more appropriate where there was a complete dataset and a balanced design, i.e. a similar number of observations in each of the factor. If there are insufficient data, particularly in one factor, the ANOVA procedure may fail and here REML (residual maximum likelihood) was used. The REML algorithm allows analysis of linear mixed models i.e. linear models that can contain both fixed and random effects. In some applications these are known as "multi-level" models. It can thus be used to analyse unbalanced designs with several error terms (which cannot be analysed by ANOVA). ANOVA and REML were used to evaluate the significance of each factor and all possible interactions on the feedstock characteristics.

REML was also used to quantify the total variation explained in each feedstock characteristic by the full model – this tells us how much of the variation in a particular characteristic is explained if we have information about the factors included in the sampling design, for example the climate zone, soil type, harvesting time and storage. The RSQ value for the model fitted using site factor information is calculated relative to the very simplest situation where we have no information about the site factors. In essence the RSQ value is the improvement on a scale of 0 to 100%. The relationships between provenance information (e.g. soil properties, site characteristics, and crop management) and feedstock characteristics were investigated by correlation analysis. Correlation coefficients were investigated in two ways: using the actual numeric values, which gives Correlation Coefficients, or the ranks, which gives Spearman Rank Coefficients. In the latter approach, the values for each of the variables to be related are ordered from the highest to lowest value with the value one assigned to the top ranked site. The rankings of the sites for the variables being related are then compared. In situations where there only a few pairs of values to be related or the relationship deviates from being linear, the Spearman correlation procedure is more appropriate.

In Study 2, the variation in the *Miscanthus* and willow SRC feedstock characteristics found between sites was compared with the variation within individual fields, by expressing the variation in each as a percentage of the total variation and then comparing the percentages. In addition, to visualise the variability between and within sites, the sampling points at each site were mapped, and then the values of selected feedstock characteristics were overlaid, with the size of each point scaled to reflect the magnitude of that particular parameter (See Appendix 4).

For Study 4 on the impact of pelletisation, insufficient data were available for any statistical analysis as it was determined during the study that additives had been used during the pelletisation process, distorting the results (further detail is given in Section 11.2).

2.6.4 Structured analysis and correlations

The following statistical processes were undertaken:

1. Structured analysis. This investigated the impacts of one or more of climate zone, soil type, harvesting time and storage (and combinations thereof) on feedstock characteristics. Identified effects (both main effects and interactions) that were not significant, i.e. with $p>0.05$ (which is a common threshold used in biological experiments), were not statistically analysed any further, though they are discussed, where relevant, in Section 14. Effects that were significant ($p<0.05$) and very highly significant ($p<0.001$) have been highlighted and discussed.

2. For each statistically significant feedstock impact identified in the structured analysis, each main effect and any interaction(s) were reviewed in relation to analytical and operational criteria. Two sifts were carried out:

    i) Analytical review

        a. the analytical limit of detection – impacts were not interpreted further if the majority of the data were at the limit of detection (LOD), on the grounds that any variation between these data are misleading because any values that were below the LOD were assumed to be present at the LOD, even though they were probably lower.

        b. the analytical error reproducibility – impacts were not interpreted further if the means of the statistically significant effects were closer than the normal level of reproducibility achieved by different accredited labs when subsamples of the same original material are analysed (as defined by the relevant standards).

    ii) Operational relevance – impacts were not interpreted further if the differences between means of the statistically significant effects would make no operational difference, usually because the values were all well below important thresholds.

    For some feedstocks, the low number of samples for some of the experimental combinations also reduces confidence on the reliability of the identification of a factor as being statistically significant.

3. Correlation analyses of feedstock characteristics and soil properties and some site provenance data were tabulated. To assist the reader, each table was colour coded to highlight individual correlation thresholds where variations in the soil properties explained at least 50% or 80% of the variation in feedstock characteristics (see Appendix 5). Correlations below the 50% threshold were not investigated further but are discussed, where relevant, in Section 14.

2.6.5 Thresholds used to identify significant results

Throughout the report particular thresholds have been chosen to flag which effects were statistically significant and focus the subsequent presentation and discussion.

Statistical analysis was used to evaluate the probability of a particular effect happening by chance alone. Effects were considered as not significant if the probability of it happening by chance alone was more common than 1 in 20, i.e. with $p>0.05$, whereas effects that were less common, i.e. with $p<0.05$, were considered worth further discussion. For the structured analyses, further clarity was provided by differentiating the level of significance into those with

p<0.05 and >0.001, i.e. there was a probability of between 1 in 20 and 1 in 1000 that the effect was due to chance alone, and those with p<0.001, i.e. there was a probability of less than 1 in 1000.

When evaluating the relationships between feedstock characteristics and soil analysis information, any instances where the variation in soil information explained less than half of the variation in feedstock characteristic, i.e. where the regression coefficient was between -0.7 and +0.7 (less than 49 % of the variation explained) were not investigated further. Where a correlation (positive or negative) was noted, this was further differentiated into a medium correlation (49 to 81% of the variation explained), and a high correlation where more than 81% of the variation was explained).

In Study 2, the variation in feedstock characteristics found between sites was compared with the variation within sites. For simplicity, the results were grouped into three categories on the basis of the ratio of the variances:

- between site : within site variance was greater than 2:1
- between site : within site was roughly 1:1
- between site : within site was less than 1:2

3 Key Parameters and Justification

3.1 Fuel parameters

For all conversion technologies, proper matching of the fuel and equipment is important. Failure to understand the probable impacts of the feedstock on the system is likely to result in reduced efficiency, lower availability, increased OPEX and increased emissions. Different conversion technologies will have different acceptable levels for each feedstock parameter. These limits will depend on a number of factors, such as steam parameters and technology type and will tend to be more restrictive for those technologies offering the highest quality outputs (e.g. highest efficiency or specific conversion products).

The most common fuel analyses undertaken can be divided into six main categories; proximate analysis, ultimate analysis, trace element content, ash composition, ash fusion temperatures and physical properties. As it is generally prohibitively expensive to undertake all these analyses on every sample, for commercial operations the analysis suite will be tailored according to which parameters are considered most critical to the safe and efficient use of the conversion system and the variability of the feedstock. Additional analyses may also be included for fuels with particular risks, for example metallic aluminium analysis for waste wood, but for this project this was not needed. For the purpose of this study, the analysis options were divided into the groups as follows:

A Proximate and ultimate analyses (moisture, ash, volatile matter, net calorific value, gross calorific value, sulphur, chlorine, carbon, hydrogen, nitrogen)

B Ash composition (SiO_2, Al_2O_3, Fe_2O_3, TiO_2, $CaCO_3$, MgO, Na_2O, K_2O, Mn_3O_4, P_2O_5, BaO) plus trace metals (Ba, Be, Cr, Co, Cu, Mo, Ni, V, Zn)

C Extended trace metals (Hg, Pb, Cd, As, Se, Sb)

D Halides (bromine and fluorine)

E Ash fusion temperatures.

The extent of analysis for each of the feedstock types and different experiments is shown in Table 3-1. For the in-field variation studies (Study 2) and the analysis of leaves (Study 3), all samples were analysed for all analysis groups A to E. All other samples (Study 1) were analysed for groups A, B and E, but only one of each set of three replicates was analysed for the extended trace element suite (C), plus halides (D). The justification for this reduced analysis frequency was the increased cost of analysis for the extended trace metals suite and the halides, reflecting the four additional analysis methods required to determine these elements at the very low concentrations expected in biomass (see Deliverable D2 for analysis methods). The original proposal did not specify any analysis for groups C and D for the stored samples (as it was assumed the main changes would be in the proximate and ultimate analysis). However, the first harvests of stored poplar SRF and spruce SRF samples (taken in April and March respectively) were in fact analysed for the normal pattern of analysis (A, B and E on all samples and C and D on one sample in each set of three replicates). The second harvest was only analysed for analysis groups A, B and E. Pellets of *Miscanthus* were collected at their processing plants both before and after pelletising (Study 4) and were analysed for the full suite of A to E, plus bulk density.

It is industry practice to express the majority of species on a dry fuel basis, allowing easy comparison between feedstocks, but other bases are also used; in particular the proximate analysis is often compared on an "as received" (wet fuel) basis for moisture and net calorific value (NCV) and dry, ash-free basis for gross calorific value (GCV) and volatile matter (VM). Note that in most of the figures the data are presented on a dry basis (mg/kg or % weight in the fuel), however for the statistical analysis the major fuel elements (C, H, N, S, Cl) were expressed on a dry, ash-free basis to enable any fundamental changes in chemical composition to be examined without being impacted by changes in ash.

Table 3-1: Analysis undertaken on each feedstock

Feedstock	Analysis Group (✓ = all samples, x = not done, 1/3 = one in three replicates)				
	A	B	C	D	E
STUDY 1					
Miscanthus fresh and stored	✓	✓	1/3	1/3	✓
Willow SRC fresh and stored	✓	✓	1/3	1/3	✓
Poplar SRC fresh	✓	✓	1/3	1/3	✓
Poplar SRF freshly harvested	✓	✓	1/3	1/3	✓
Poplar SRF Apr harvest 3 month stored (as roundwood)	✓	✓	1/3	1/3	✓
Poplar SRF Jul/Aug harvest 3 month stored (as roundwood)	✓	✓	x	x	✓
Spruce SRF freshly harvested	✓	✓	1/3	1/3	✓
Spruce SRF Mar harvest 3 month stored (as roundwood)	✓	✓	1/3	1/3	✓
Spruce SRF Jun harvest 3 month stored (as roundwood)	✓	✓	x	x	✓
STUDY 2					
Miscanthus in-field variation	✓	✓	✓	✓	✓
Willow SRC in-field variation	✓	✓	✓	✓	✓
STUDY 3					
Willow SRC leaves	✓	✓	✓	✓	✓
Poplar SRF leaves	✓	✓	✓	✓	✓
STUDY 4					
Miscanthus raw material	✓	✓	✓	✓	✓
Miscanthus pellets	✓	✓	✓	✓	✓

Many of these analyses are of limited interest for many conversion technologies, particularly for clean feedstocks, but are analysed in conjunction with other components. Some of the trace elements in particular were consistently found at levels below (or close to) the limit of detection in some or all of the feedstocks in this project, restricting detailed review. Of those components which do warrant in-depth investigation, some are key fuel quality parameters, others may affect boiler performance (for example through impacts on slagging and fouling,

corrosion and bed agglomeration) while some are of environmental concern. Using these criteria, prioritisation of the analysed parameters for statistical review was determined as shown in Table 3-2.

The critical levels of these fuel components will vary depending on the conversion system and, for those of environmental concern, installed clean-up equipment; however quality standard limits for white wood pellet (currently the only biomass traded as a commodity) are discussed in Section 12.

Table 3-2: Analysed fuel parameters and their prioritisation for statistical review

Analysis Group	Parameter basis	Parameter	Priority for statistical analysis	Justification/impact on conversion systems
A - Proximate and Ultimate analysis	As Received fuel basis	Moisture content wt %	High	High moisture content will reduce combustion plant efficiency. Potential impact on fuel handling/ dustiness/ degradation in storage
		Fixed carbon wt %	Low	Calculated from other parameters – limited value
		NCV kJ/kg	High	Direct impact on size and efficiency of plant and fuel logistics
	Dry Fuel Basis	Ash wt %*	High	Impacts calorific value, plant efficiency, slagging and fouling tendencies, erosion. Ash handling systems need to be designed to deal with the expected ash quantities of ash produced. With high ash levels, fluidised bed materials may need more regular replacement.
	Dry, Ash-free basis	Volatile matter wt %	High	Volatile matter will impact on flame stability, combustion burnout performance and NOx emissions.
		GCV kJ/kg	High	Measure of fuel consistency across different feedstock samples -allows comparison without being affected by moisture and ash
		Carbon wt %*	Medium	Measure of fuel consistency across different feedstock samples - limited direct impact on plant although will affect CO_2 emissions per unit output
		Hydrogen wt %*	Medium	Measure of fuel consistency across different feedstock samples – used in NCV calculations
		Nitrogen wt %*	High	Direct impact on NO_x emissions
		Sulphur wt %*	High	Direct impact on SO_x emissions and can be corrosive in high temperature systems, but in lower temperature systems can mitigate against chloride corrosion. Acid gases also cause amine degradation in carbon capture processes.
		Chlorine wt %*	High	Implicated in corrosion mechanisms and acid gas emissions. Acid gases also cause amine degradation in carbon capture processes.
		Oxygen wt %* (by difference)	Low	Calculated from other parameters – limited value

Analysis Group	Parameter basis	Parameter	Priority for statistical analysis	Justification/impact on conversion systems
Category B - Trace elements	mg/kg dry fuel	Barium	Medium	Limited environmental/plant impact
		Beryllium	High	Emissions are of environmental concern
		Chromium	High	Emissions are of environmental concern
		Cobalt	Medium	Limited environmental/plant impact
		Copper	High	Emissions are of environmental concern
		Molybdenum	Medium	Limited environmental/plant impact
		Nickel	High	Emissions are of environmental concern
		Vanadium	Medium	Limited environmental/plant impact
		Zinc	High	Emissions are of environmental concern. Implicated in corrosion mechanisms. Metallic zinc can melt in combustion systems and block air nozzles (not expected to be an issue for clean feedstocks)
Category C - Trace elements	mg/kg dry fuel	Antimony	High	Emissions are of environmental concern
		Arsenic	High	Emissions are of environmental concern. Poison for NO_x reduction catalysts.
		Mercury	High	Emissions are of environmental concern.
		Selenium	High	Emissions are of environmental concern
		Cadmium	High	Emissions are of environmental concern
		Lead	High	Emissions are of environmental concern. Can have an impact on plant integrity. Elevated levels in the ash and boiler deposits may also be of occupational health concern to plant workers
Category D - Halides	mg/kg dry fuel	Bromine	High	Forms acidic gases which are of environmental concern and may be involved in corrosion mechanisms. Also believed to damage bag-house filters but may aid in mercury capture mechanisms. Acid gases also cause amine degradation in carbon capture processes.
		Fluorine	High	Forms acidic gases which are of environmental concern may be involved in corrosion mechanisms. Acid gases also cause amine degradation in carbon capture processes.

Analysis Group	Parameter basis	Parameter	Priority for statistical analysis	Justification/impact on conversion systems
Category B - Ash forming elements in fuel	mg/kg dry fuel - back-calculated from measured concentration of the oxide in ash	Aluminium	High	Alumino-silicate in the ash may mitigate alkali-metal mediated corrosion/ slagging/fouling
		Calcium	High	Principal biomass ash component - impacts on slagging. May help acid gas abatement
		Iron	High	High levels of iron in ash can cause slagging, but it is normally present at low concentrations in biomass
		Potassium	High	Key concern for plant corrosion and slagging. Alkali metals may also result in formation of fine particulate matter which is an issue for emissions and for amine-based carbon capture processes. Poison for NO_x reduction catalysts.
		Magnesium	High	Magnesium in the ash may mitigate alkali-metal mediated corrosion/ slagging/fouling
		Manganese	Medium	Manganese levels are normally so low in biomass ash as to have no significance
		Sodium	High	Key concern for plant corrosion and slagging. Alkali metals may also result in formation of fine particulate matter which is an issue for emissions and for amine-based carbon capture processes.
		Phosphorous	High	Poison for NO_x reduction catalyst. Phosphorous may also be implicated in corrosion.
		Silicon	High	Alumino-silicate in the ash may mitigate alkali-metal mediated corrosion/ slagging/fouling. Silica (quartz) may cause abrasion and erosion.
		Titanium	Medium	Titanium levels are normally so low in biomass ash as to have no significance
Category E -Ash fusion temperatures	Reducing Atmosphere, °C	Initial deformation	Low	Data unsuitable for statistical analysis. Ash fusion temperatures provide an indication of the likelihood of ash slagging and bed agglomeration
		Softening	Low	
		Hemisphere	Low	
		Flow	Low	
	Oxidising atmosphere, °C	Initial deformation	Low	
		Softening	Low	
		Hemisphere	Low	

Analysis Group	Parameter basis	Parameter	Priority for statistical analysis	Justification/impact on conversion systems
		Flow	Low	
Category B - Ash Oxides	Normalised ash oxides, %wt in ash (calculated from measured ash oxides to normalise for SO_3 and express Ca as $CaCO_3$)	Al_2O_3*	High	Alumino-silicate in the ash may mitigate alkali-metal mediated corrosion/ slagging/fouling.
		BaO*	Medium	Barium levels are normally so low in biomass ash as to have no significance
		$CaCO_3$*	High	Calcium is often the most dominant macroelement in biomass ash and can be implicated in slagging and fouling. May help acid gas abatement
		Fe_2O_3*	High	High levels of iron in ash can cause slagging, but it is normally at low concentrations in biomass
		K_2O*	High	Key concern for plant corrosion and slagging. Alkali metals may also result in formation of fine particulate matter which is an issue for emissions and for amine-based carbon capture processes. Poison for NO_x reduction catalysts.
		MgO*	High	Magnesium in the ash may mitigate alkali-metal mediated corrosion/ slagging/fouling
		Mn_3O_4*	Medium	Manganese levels are normally so low in biomass ash as to have no significance
		Na_2O*	High	Key concern for plant corrosion and slagging. Alkali metals may also result in formation of fine particulate matter which is an issue for emissions and for amine-based carbon capture processes.
		P_2O_5*	High	Poison for NO_x reduction catalysts. Phosphorous may also be implicated in corrosion.
		SiO_2	High	Principal ash component - Alumino-silicate in the ash may mitigate alkali-metal mediated corrosion/slagging/fouling. Silica (quartz) may cause abrasion and erosion.
		TiO_2*	Medium	Titanium levels are normally so low in biomass ash as to have no significance
Derived	Alkali Index	kg(Na_2O + K_2O)/GJ	High	Measure of slagging risk in combustion systems

*Also included in D4 on other bases but these are considered to be lower priority for statistical review as they are less comparable

As well as analysing for specific components, it is common practice to use these data to predict the behaviour of the feedstock in different conversion systems. This ranges from prediction of acid gas emissions from the concentrations of the acid-forming elements in the fuel to analysing more complex systems such as the formation of slagging deposits. Numerous indices have been developed to predict the impact of different fuel components on issues such as slagging, fouling and corrosion, for example the base-acid ratio (Equation 3-1) and the related slagging index (Equation 3-2). However, for the most part these have been developed based on experience in coal-fired plant.

Equation 3-1: Base/Acid ratio (species expressed as percentage weight in ash)

$$\frac{B}{A} = \frac{Fe_2O_3 + CaO + MgO + K_2O + Na_2O}{SiO_2 + Al_2O_3 + TiO_2}$$

Equation 3-2: Slagging index (R_s)

$$R_s = \frac{B}{A} \times sulphur\ (\%dry)$$

For biomass, the principal ash components and the mineral associations of different elements can be very different to those of coal, so these indices are less effective in predicting potential issues in biomass combustion. One index that does appear to be effective for predicting slagging behaviour in biomass systems is the alkali index (AI), which is based on the alkali mass input per unit energy (Equation 3-3) [Miles *et al.*, 1995]. For this, values below 0.17 indicate a low fouling/slagging risk, for those between 0.17 and 0.34 fouling/slagging is considered to be probable and above 0.34 fouling/slagging is certain. As the AI is often included in boiler fuel specifications, it has been calculated for the feedstocks in this project and included in the statistical review. It should be noted however that during operation, slagging propensity and rates will also be influenced by other factors such as the boiler design and operation, the chemical form of slagging elements and the presence of other materials (additives, bed materials) which may react with the ash.

Equation 3-3: Alkali index

$$AI = \frac{kg(Na_2O + K_2O)}{GJ\ (GCV)}\ \text{(dry fuel basis)}$$

3.2 Soil and site parameters

As well as the feedstock samples, a (composite) soil sample was collected for each site in Study 1 to 3 and submitted for analysis. This included evaluation of the main soil components (sand, silt, clay, and organic matter), which provided a soil classification for each site (see Figure 3-1), trace metals (soluble and total), pH, and cation exchange capacity (CEC); the rationale for these choices was described in detail in D2.

The analyses performed were as follows:

- Percentage in soil of:
  - Clay
  - Silt
  - Sand
  - Organic Matter (% weight in dry soil)
- Soil Classification
- Soil type (Medium, Light, Heavy)
- pH
- C.E.C (cation-exchange capacity
- Available elements:
  - P, K, Ca, S, Mn, Cu, B, Zn, Mo, Fe, Na, Co, N, Cl, Se
- Lime requirement
- Total elements
  - Cu, Zn, Pb, Ni, As, Cd, Hg, Cr
- Predictions based on soil information:
  - Available water levels
  - Drainage rate
  - Inherent fertility
  - Potential C.E.C
  - Leaching risk
  - Warming rate

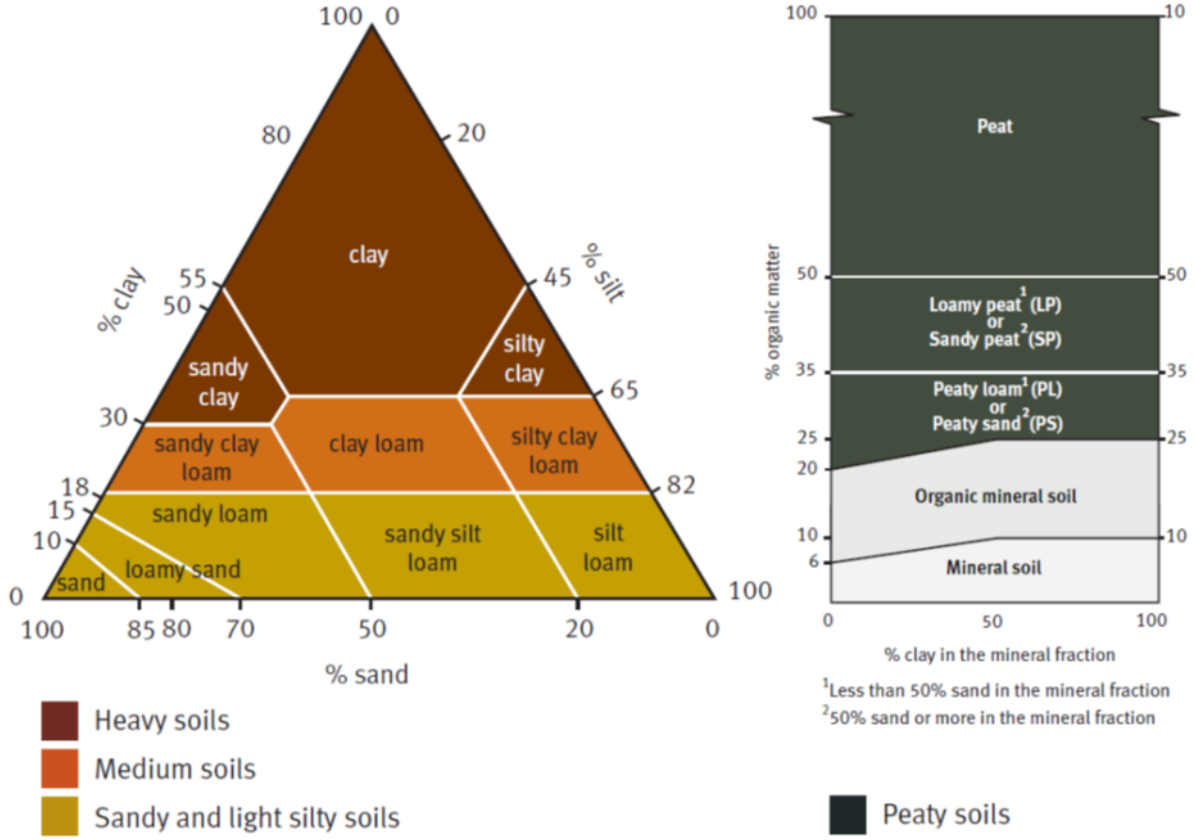
Results of all soil analysis can be found in the D4 database.

In addition, provenance data on the management of the site was also obtained where available, with a list of parameters agreed at the start of the project. Information was collected directly from the growers and/or the supplying company (see Appendix 2 for a complete listing of the parameters collected).

The rationale for each individual parameter was described in detail in D2 but some key choices are explained below. It was originally anticipated that provenance information on the level of soil drainage, degree of slope, and level of stone content, which influence chemical retention within the soil, could help to indicate whether certain elements would be prone to leaching, and consequently there would be a relationship between levels of certain elements in the feedstock and provenance data. It was also expected that certain site factors could affect certain aspects of the feedstocks' growing habits (and so affect feedstock characteristics), such as the timing of senescence, or starting of growing. Consequently biomass samples in the same climate zone may be different simply because they were grown in different microclimates.

The project team also investigated site management practices that could have an impact on the produced feedstock material. Provenance information was collected to cover a wide range of possible scenarios and possible interactions – a full justification for the parameter selection was given in D2.

Figure 3-1: Soil texture classification for mineral soils and for soils with high organic matter content (Taken from: Environment Agency, Think Soils manual Chapter 2)



The breadth of provenance information covered by the sampling achieved within the project can be summarised as follows. Soil for the *Miscanthus,* willow SRC and poplar SRC/SRF sites sampled in Study 1 to 3 all largely fell within two main mineral soil classifications of light and medium mineral soils, whereas the spruce SRF sites all had light soils. For spruce SRF, all but one of the sites fell within the organic and peat soil classifications; in contrast only two of the twelve *Miscanthus* sites were organic classification soils, and only one of the willow leaves sites was on an organic soil. A soil is classified as organic when the organic matter content is typically above 6% of the whole, but if the clay content of the soil exceeds 50% then the organic matter percentage has to exceed 10% before the soil can be classified as an organic soil type. Only the spruce SRF was found growing on peaty soil types; peat soil classification starts at 20% organic matter content of the soil, as shown in Figure 3-1.

Within the light and medium soil classifications there are eight recognised sub-classifications, (five in light soils and three in medium soils, see Figure 3-1). In the project all five of the sub-classes of light soils and two of three sub-classes of medium soils (sandy clay loam and clay loam) were represented.

Questions were asked around site preparation, establishment and management, but in general, for each feedstock, the methods used were fairly uniform.

A critical requirement of the project team has been to sift this wealth of provenance data and the potential analyses to focus on the key points. Provenance data were selected for statistical analysis on the basis of whether the information obtained was:

- sufficiently different to warrant statistical analysis – for example almost all soils/sites were reportedly prepared and treated in the same way for establishing individual feedstocks, so trying to ascertain any correlation differences between and within feedstock characteristics and the soil management aspects was not possible.
- robust from a practical point of view – for example, while data on sewage sludge application was requested, the data obtained was often incomplete.

Table 3-3 shows the suitability of the main categories of provenance information for statistical evaluation while Table 3-4 gives the justification for its collection and the team's decision on whether it warranted statistical analysis.

Table 3-3: Suitability of provenance information for statistical evaluation.

Yes	**No**
Planting density (SRF) Clay, silt sand and organic matter % in soil Soil classification Age of planting pH Elements analysed (if above the limit of detection) CEC (Cation Exchange Capacity)	Fertiliser additions and type Sewage sludge treatment Clone/variety Pesticide applications Ground preparation Available water Lime requirements

Table 3-4: Analysed soil and site provenance parameters and their prioritisation for statistical analysis

Provenance Data Collected	Reasoning for provenance data collection	Statistical value
Fertiliser applied and type	Fertiliser products as bagged artificially produced or organic materials (manures, sludges, composts) are expected to have the potential to impact on elements both within the plant and the soil. Organic matter (OM) content could also be affected by an application of organic fertiliser.	After reviewing the collected fertiliser data, it was decided the applied fertiliser figures should not be included in the overall statistical evaluation, as there was no supporting information to enable a review of the management process.
Sewage Sludge treatment	To understand if applications of sludge elements, namely macro soil elements (N, P, K, Mg) are affected within the plant, in addition to heavy metal content, and also Organic matter (OM) content	Due to varying levels of retrievable information regarding any applied sewage sludge to some Willow SRC crops no statistical review was performed. A review of the data showed there was limited information on what was applied and when, hence finding a correlation was not possible.
Clone/variety	This information was collected particularly for the willow SRC and poplar SRC, to ensure that (for this phase of the study) the varieties sampled at each site were consistent. A subsequent trial, funded as a contract variation, is evaluating clonal differences of willow SRC.	Variety data was collected for all the species, with care taken to minimise the effect of varietal differences in order that the main factors, such as soil type and storage, were not obscured. Variety information was therefore not appropriate for statistical analysis.
Pesticide applications	Understanding if there have been any consistently applied pesticides to any of the plant species was important in ruling out any possible contamination from this operational process. All sites were reported to have been treated with some form of pesticide initially at the point of establishment for weed control purposes, but none were continually treated whilst growing.	It was decided that the collected provenance data, although interesting, was not of any statistical value to the overall project.

Provenance Data Collected	Reasoning for provenance data collection	Statistical value
Ground Preparations	These data were collected to understand if there were any unusual land cultivations which had been performed which could have a potential impact on soil drainage and soil nutrient availability of elements.	All sites were reportedly treated using similar methods with regards to initial ground preparations, so the data has been excluded from further statistical evaluation.
Planting Density	The planting density of an individual species can have a significant impact on the growth characteristics. If a planting density is high then the growth of the planted material will be very different (thinner stems with higher bark to wood ratio) than if a lower density planting were to be used.	For the annual and short-cycle crops, planting densities were fairly consistent. Planting density was examined for SRF species.
Clay, Silt, Sand and Organic Matter (OM) % in soil	Understanding the clay, silt, sand and organic matter (OM) content within a soil is important in helping to understand the potential capacity for achieving element exchange between the plant and the soil.	These data have been included in the overall statistical analysis of correlations between feedstock characteristics and soil type/classification.
Soil Classification – including higher classification of (Light, Medium and Heavy)	Soil classification is based on the ratios of clay, silt, sand and organic matter within a soil. The soil classification chart used is shown in Figure 3-1, which identifies eleven textural classes and three organic classes. The textural classes are grouped further into Light, Medium and Heavy soils based on their mineral and/or organic soil classifications.	The soil types have been classified depending on their composition, and classified for ease of statistical evaluation, as: Light, Medium and Heavy for most feedstocks and Mineral, Organic and Peat soils for the spruce SRF. These classifications were used within the structured analysis.
Available Water	Available water is partly linked to the soil classification data, but also links to local rainfall levels. If the local available water levels are low then this could significantly impact on the chemical composition of the biomass, and also the nutrient availability to the plant. Likewise if the local water availability is in excess, then different soil conditions may occur meaning the uptake of nutrients could be seriously affected, as could the loss of elements caused by leaching both from the soil and the biomass.	Insufficient supporting data were available so a full evaluation was not possible.

Provenance Data Collected	Reasoning for provenance data collection	Statistical value
Age of planting	This was requested from the producers because we wanted to assure we were comparing wherever possible similar aged plant material for the same species in different locations. If we used different aged material, with different varieties, in a wide range of different circumstances then trying to correlate any relationships would be almost impossible.	Although the intention was to use similarly aged materials to minimise the impact of this variable, the sampled material did vary significantly in age and so could be reviewed statistically
pH	The soil pH is required to understand any potential limitations or lock up of certain elements in the soil.	Soil pH has been included as part of the overall statistical analysis of correlations between feedstock characteristics and soil properties
Elements analysed	The elements analysed for the project were the most common for plant health status, and those elements which are linked to both desirable and undesirable elements seen within biomass composition when being combusted. The main soil elements were analysed were; P, K, Mg, Ca, Na, Fe, Zn, Mn, Cl, S, N, plus Cu, B, Mo, Co, Se, Pb, As, Ni, Cd, Hg, Cr.	All elements that were present above the Limit Of Detection (LOD) have been statistically analysed for correlations between feedstock characteristics and soil properties
Lime requirement	The lime requirement figure was included as part of the overall soil analysis process.	Any relationships of interest were already covered by the level of pH, which has been included in the statistical review process.
CEC (Cation Exchange Capacity)	The CEC of a soil helps to determine a soil's capability to hold and offer elements to a plant. The higher a CEC of a soil the more readily elements are able to be transferred within the soil and between the soil and the plant.	It was considered and discussed as being an interesting piece of information for each of the different soils collected and included in statistical correlations

4 Overview of feedstock characteristics

4.1 Results

4.1.1 Sampled sites

The sampling locations for all feedstocks are shown in Figure 4-1. Maps for each species identifying where the different studies were undertaken are presented in the corresponding chapters. Details of the individual studies are given in Table 4-1.

Figure 4-1: Sampling locations for all feedstocks

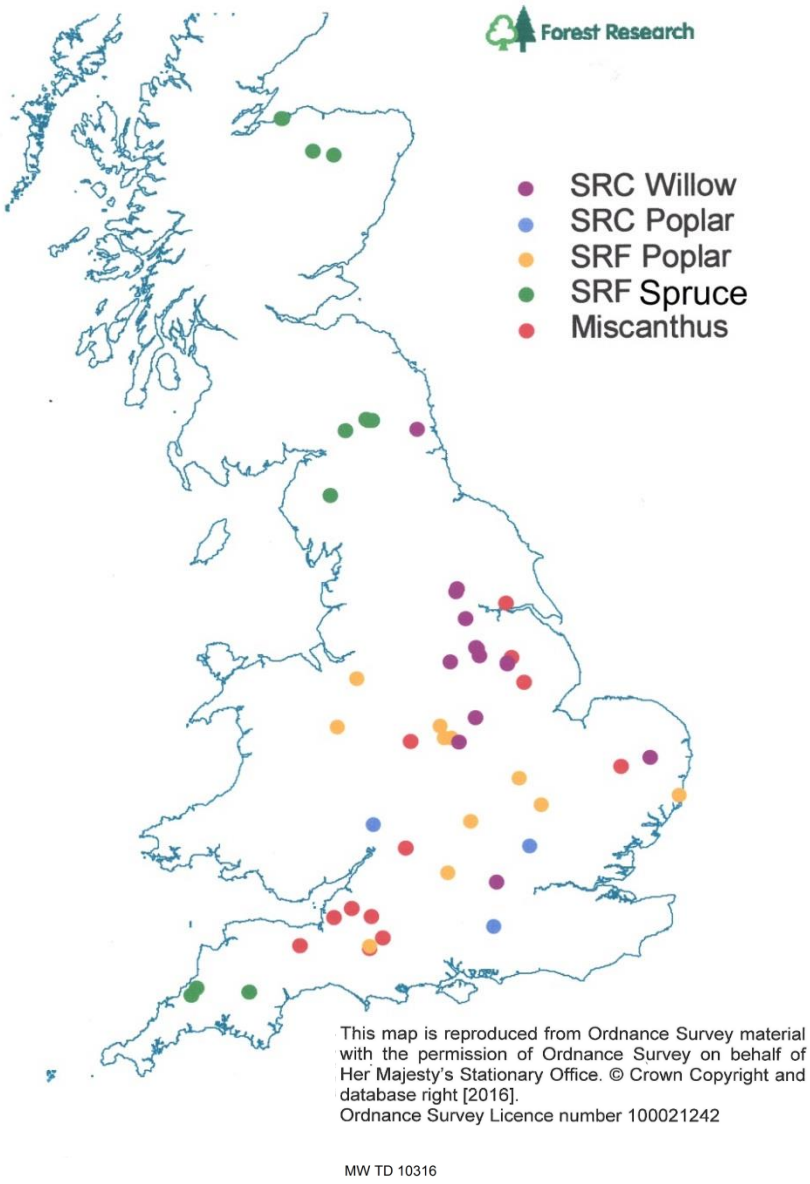


Table 4-1: Overview of experiments

Feedstock	Harvest time	Plant part	Time of sample	Final number of sites	Notes and additional information
Study 1: Variability and its determinants					
Miscanthus	February to April	whole	at harvest in-field prior to baling 1 month stored as bales	12	One variety of *Miscanthus* (*Miscanthus x giganteus*) was analysed. Crops were sampled at the usual, commercial harvest time. In practice this was determined by local weather conditions, the state of the crop, availability of contractors and the ground conditions. The initial samples were taken immediately after the crops were cut. The second samples were taken immediately before the crop was baled to represent the condition of the crop at baling. This was after a period of lying in the swath in the field to allow further drying. Rain gauges were used to assess the amount of rain during this period to allow the potential for any leaching of minerals to be assessed; in 3 of the 12 cases the gauge was destroyed during baling. In 3 cases where the crop was baled immediately, or within a few days, this sample was not taken. The third samples were taken after the baled crop had been stored for 1 month.
Willow SRC	Feb to May	whole	at harvest 1 month stored as chips	7	Many varieties of willow have been planted for SRC crops over the past 25 years, with at least a dozen commonly planted, and typically five mixed in small groups throughout a field. A representative mix of all varieties within a crop was obtained by mixing multiple scoops of the chips immediately after harvest. Willow SRC crops were sampled at the usual, commercial harvest time, again determined by local weather conditions, ground conditions, and the availability of specialist harvesting contractors and machinery. The coppice was beginning to emerge from dormancy. Some stems were still dormant, and some were flushing but the amount of leaf material was low. The first samples were taken immediately after harvest, from the chipped (in one case billeted) material. The samples were made up from 40 separate scoops of chips, thoroughly mixed and sub-sampled to provide a representative mix of the willow varieties present in the crop. The second samples were taken from the chip pile(s) after one month in storage. Again 40 separate scoops were taken from different positions within the stack, thoroughly mixed and sub-sampled.

Feedstock	Harvest time	Plant part	Time of sample	Final number of sites	Notes and additional information
Poplar SRC	June	whole	at harvest	3	Only one commercial poplar SRC crop was still available by the time sample collection started, so this was supplemented by two research poplar SRC crops. While these samples were taken to accompany the main project, it has been assumed that they are not representative of a typical commercial poplar SRC crop.
Poplar SRF	April July to August	trunk tops	at harvest 3 months stored	11	A large number of different poplar clones have been planted, with typically 16 on an individual site. We therefore selected a core of three different clones (Gaver, Ghoy, Gibecq) that were all present on all but three of our test sites, and sampled four examples of each. Trees were felled and divided into three components: the main stem, up to a diameter 7cm, and the tops <7 cm diameter with attached branches and leaves when present. The stem samples were not separated into bark and wood. To ensure that representative samples were analysed, sample disks were cut from two heights within the stem, and both the tips and bases of tops were sampled (from different pieces). Harvest 1 was in April when the trees were beginning to emerge from dormancy. Some were still dormant, and some were just flushing but the amount of leaf material was very low. Harvest 2 was taken in July and early August, by which time the trees were in full leaf and consequently the “tops” samples included a significant amount of leaf material. Stem billets and remaining tops were transported to a compound at Thetford for safe storage for 3 months. The stems were stacked on bearers, and the tops placed on top of the stacks. After 3 months they were sampled again to assess the effect of this period of storage. In order to mimic typical commercial practice, no attempt was made to prevent the loss of leaf material, and consequently these are likely to have been substantially lost (from the second harvest) by the time of the second sampling.

Feedstock	Harvest time	Plant part	Time of sample	Final number of sites	Notes and additional information
Spruce SRF	March June	trunk tops	at harvest 3 months stored	12	Trees were felled and divided into three components: the main stem, up to a diameter 7cm, the tops <7 cm diameter with attached branches and needles, and the bark. Unlike the poplar SRF, samples for analysis were taken separately from the bark and the wood of the main stem. To ensure that representative samples were analysed, sample disks were cut from two heights within the stem, the tips and bases of tops were sampled, and bark samples were taken. Harvest 1 was in mid-March. As an evergreen conifer, the tops samples would have included needles, but the trees were in a state of partial dormancy with no newly emergent needles. Harvest 2 was in late June. As in Harvest 1, needles were present in the tops samples, however the trees would have been far more metabolically active and tops samples included new extension growth and this season's needles in addition to previous years' needles. Remaining stem billets were stacked in the forest, with the remaining tops on top, for three months after each harvest and sampled again to assess the effect of this period of storage. Samples were taken from the wood of the main stem, but no stored bark samples were taken. In order to mimic typical commercial practice, no attempt was made to prevent the loss of needles and consequently these are likely to have been substantially lost (from both harvest times) from the stored samples.
		bark	at harvest	12	Bark samples were only taken at the two harvesting times, not after storage.
Study 2: Within-field variation					
Miscanthus	March to April	whole	at harvest	3	Samples were taken from 20 random positions within the three fields of *Miscanthus* crop, immediately after harvest, at the usual commercial harvesting time. They were packaged and analysed separately.
Willow SRC	March	whole	at harvest	3	In order to ensure difference in varieties did not obscure any spatial effects, having predetermined 20 random positions within the field for sampling, an expert was enlisted to identify the nearest example of Tora, and samples were cut from this as entire, representative stems. These were taken at around the usual harvest date, but before the specific field had been harvested. The coppice was beginning to emerge from dormancy. Some stems were still dormant, and some were just flushing but the amount of leaf material was very low.

Feedstock	Harvest time	Plant part	Time of sample	Final number of sites	Notes and additional information
Study 3: Leaves					
Poplar SRF	July to August	leaves only	In full leaf	11	The same varieties of poplar were sampled for leaves as for Study 1 (i.e. Gaver, Ghoy, Gibecq). Leaf samples were collected from the poplar SRF at the same time the second harvest samples were taken, when they were in full leaf.
Willow SRC	September	leaves only	In full leaf	9	A random mix of willow varieties was sampled for leaves based on predetermined GPS waypoints in the field. Leaf samples were taken from standing SRC willow crops when they were in full leaf. All leaves were collected from each stem sampled to include leaves from both the base and tip of the stem.
Study 4: Pelleting					
Miscanthus	n/a	whole	before and after pelleting	n/a	Samples of *Miscanthus* pellets were obtained direct from the pellet manufacturer, together with samples of the raw feedstock, and analysed.

4.1.2 Major fuel parameters

This Section will present a selection of the key parameters across all the freshly harvested feedstocks. Certain feedstocks were subject to harvesting and sampling on more than one occasion to investigate the effect of different harvest times (harvest months are shown in Table 2-1); where relevant these data are displayed in different colours within the charts to highlight any changes. Note that values that have been considered to be outliers for statistical analysis have been included in Figure 4-2 to Figure 4-8 for illustration purposes, but not Figure 4-11 to Figure 4-14 (as the average values used in the latter set of graphs would have been distorted by the outliers). These graphs show the results from Study 1 & 3, and, where appropriate, an average value for each of the willow SRC and *Miscanthus* in-field variation studies (Study 2). Summary statistics for each feedstock are presented in Appendix6. Further graphs for all feedstock analysis variables are presented in Appendix 7.

The impacts of storage on the feedstock are not discussed here and are dealt with in each specific feedstock Section (where appropriate). Although visible differences associated with harvesting time are mentioned here, the impacts of harvesting time are presented and discussed in detail within the individual feedstock sections.

From an energy conversion perspective, the most important characteristic of a fuel is the available heat content or calorific value. This is often reported as a Gross calorific value (GCV) which is the total measured heat content in the fuel after bringing all the products of combustion back to the pre-combustion temperature. However, in most combustion systems the products of combustion escape as vapour and the latent heat of evaporation of water and the reaction products is not recovered. The Net calorific value (NCV) accounts for this loss and describes the realisable heat content of the fuel, and should be reported on an as received (wet) basis (ar). As the moisture (and ash) content can vary widely between different samples, it is often common practice to normalise the GCV for moisture (and ash) to compare samples on a dry (d) or dry ash free (DAF) basis. Note all percentages are expressed as a weight percentage.

Figure 4-2 illustrates the changes in DAF GCV between the different feedstocks and sub-samples of feedstock. The DAF GCV was lowest for the *Miscanthus*, the willow SRC stems and trunks of the other feedstocks, increasing in the tops and is highest in the leaves and bark. The higher DAF GCV is a reflection of the increased carbon and hydrogen contents of the tops/leaves and bark, compared to the trunk wood and *Miscanthus*. The oxidation of carbon and hydrogen provides the predominant sources of energy. It should be noted however, that although the DAF GCV was highest for the plant extremities, these parts tend to contain higher moisture and ash levels so the available energy on an “as received” basis is reduced.

Figure 4-2: Comparison of GCV (DAF) values across all feedstocks in study 1 & 2

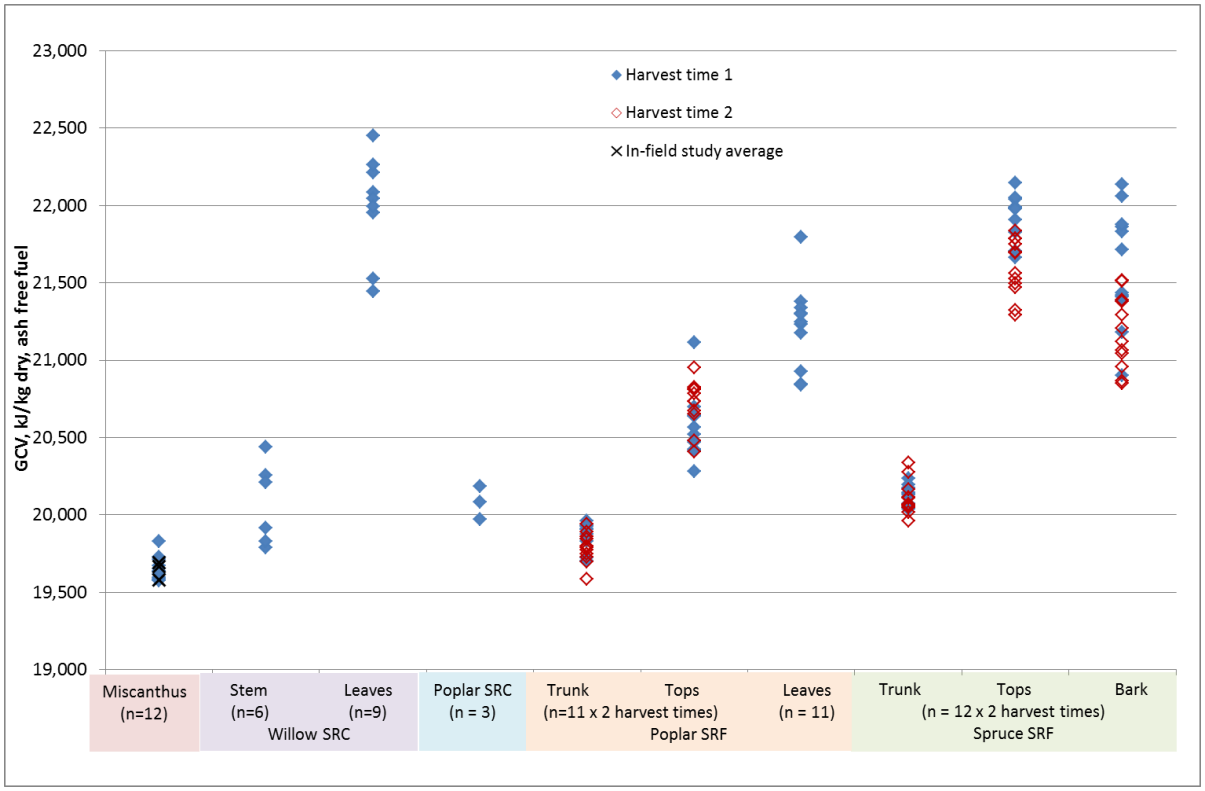


Figure 4-3 demonstrates the large variation in moisture content between the freshly harvested feedstocks. The *Miscanthus* has the lowest and most variable moisture content as harvested (possibly due to the material being more susceptible to absorbing and losing moisture according to the conditions at harvest than the woody feedstocks), whilst the trunk wood and tops contain typically 50-60% moisture with the leaves containing >60% moisture. As noted above, the realisable heat content (NCV) is strongly correlated with moisture content and Figure 4-4 displays these data; the effect of different harvest time is clear for both the SRF feedstocks. The ash content of the different feedstocks is illustrated on a dry basis in Figure 4-5 and clearly shows the very low ash levels in the trunks of the woody biomass of <2%, which increases in the tops up to 6%, with the leaves containing the highest levels at up to 10% ash (dry). Somewhat surprisingly, the dry ash content of the spruce SRF bark is comparable with that in the spruce SRF tops at 2-3%.The *Miscanthus* dry ash content is comparable with that in the tops of the woody biomass types.

Figure 4-3: Comparison of moisture (ar) values across all feedstocks in study 1 & 2

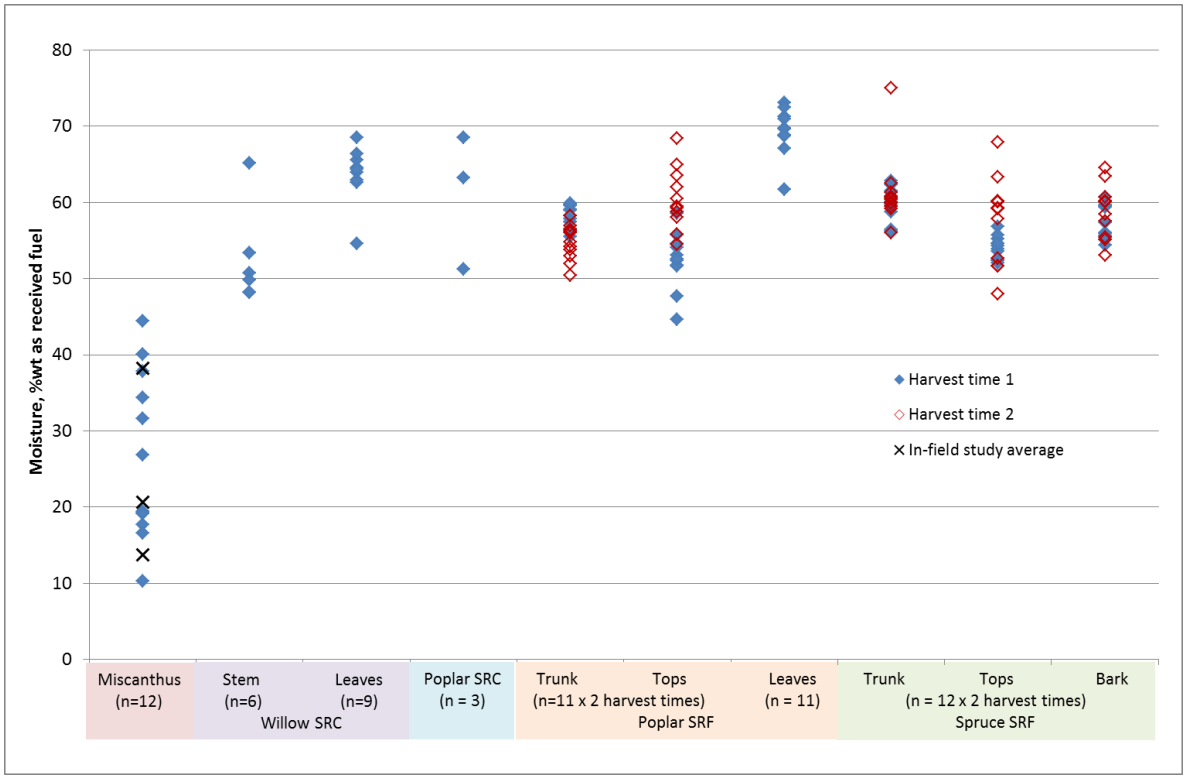


Figure 4-4: Comparison of NCV (ar) values across all feedstocks in study 1 & 2

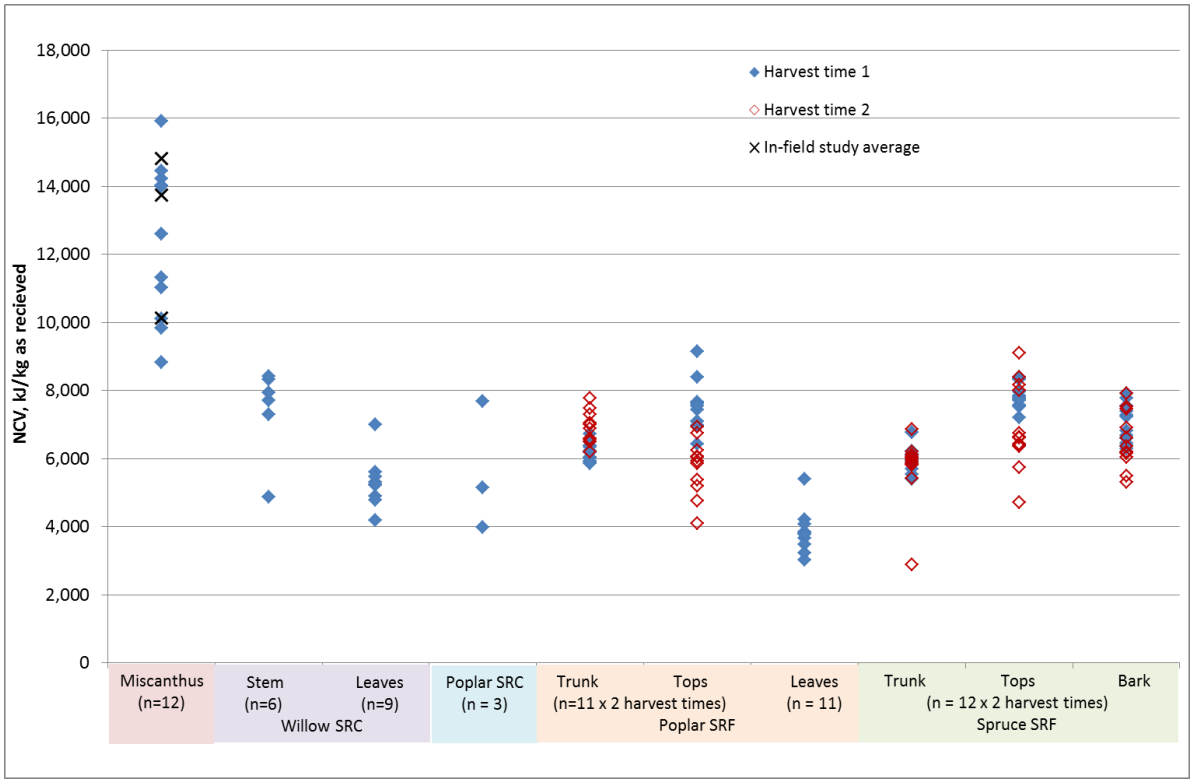
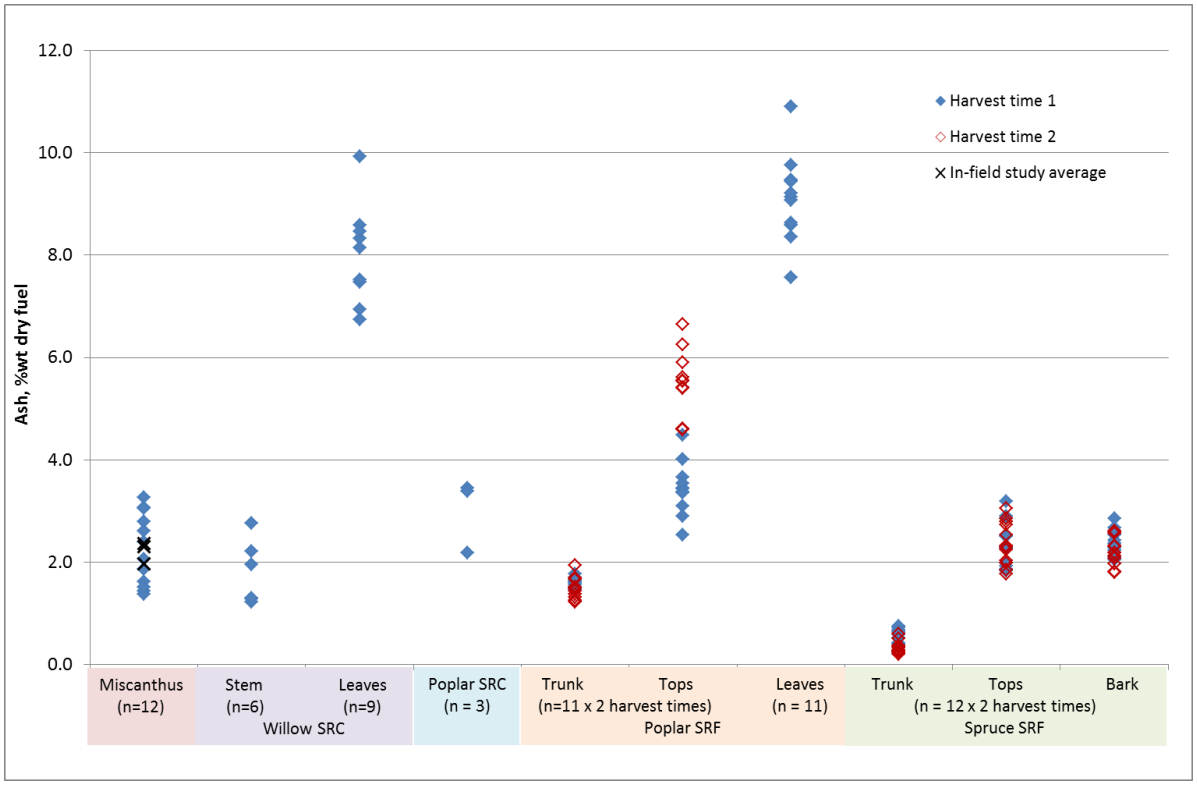


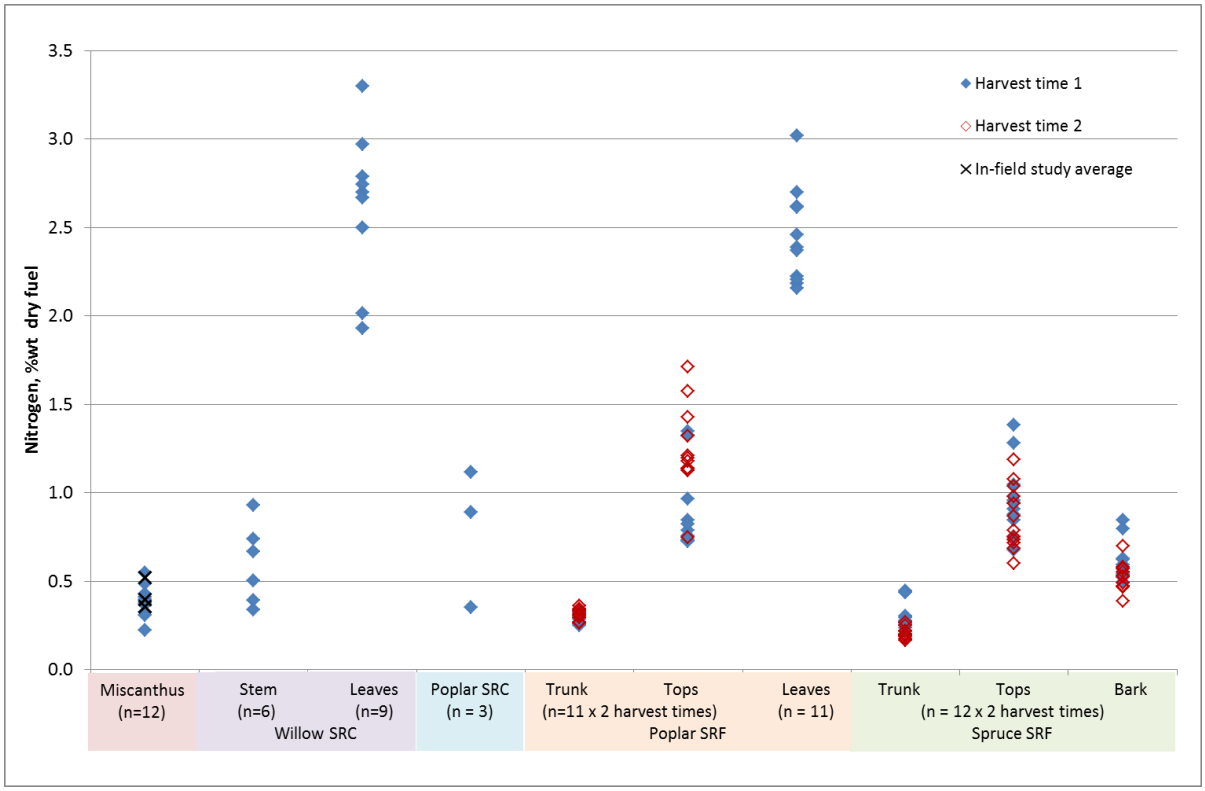
Figure 4-5: Comparison of ash (d) values across all feedstocks in study 1 & 2



Sulphur, nitrogen and chlorine concentrations in feedstocks will all impact on the environmental performance of the subsequent combustion process, and in general lower concentrations in the feedstock are preferable from this perspective. Chlorine also can play a role in corrosion mechanisms, particularly in combination with alkali metals such as potassium, although in this respect the presence of sulphur actually inhibits this reaction and so is desirable.

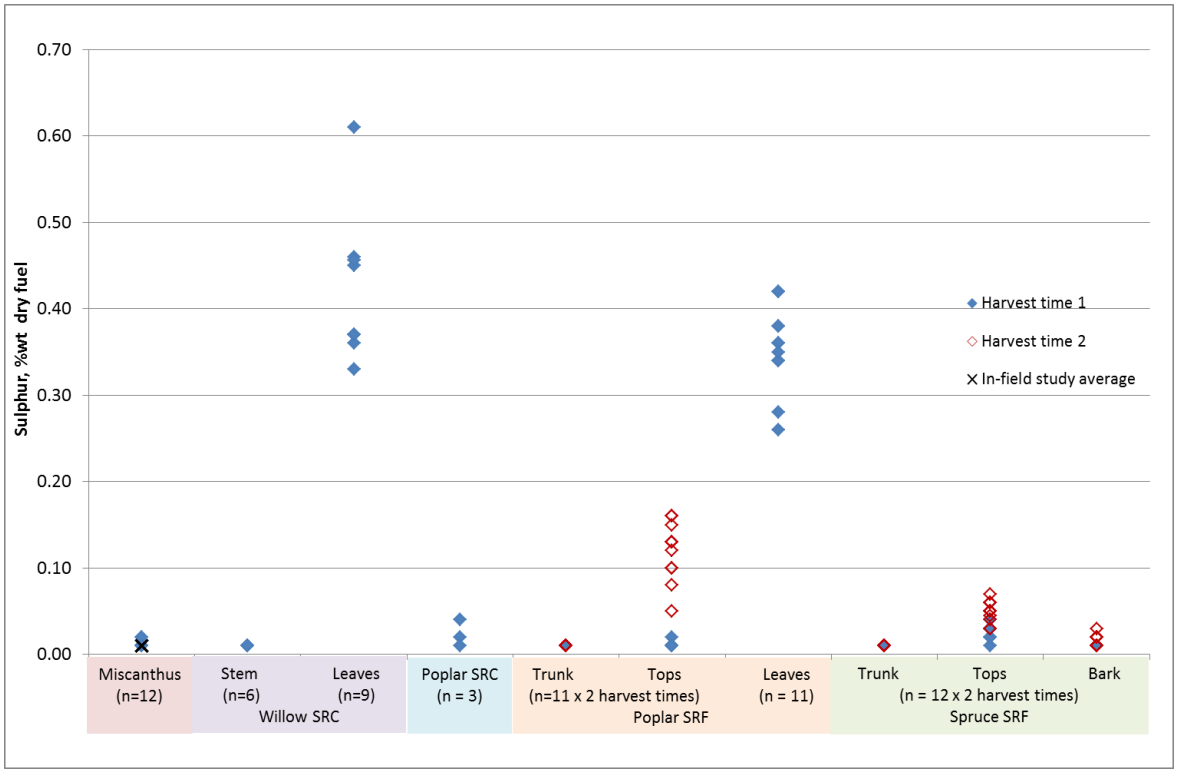
The dry nitrogen content of the feedstocks is illustrated in Figure 4-6. As with the ash, the lowest nitrogen contents are found in the trunks of the spruce SRF and the highest in the leaves of the willow SRC and poplar SRF. The nitrogen levels in the tops and bark of the spruce SRF were higher than the trunk, with the spruce tops ranging from 0.6-1.4wt% N (DAF basis), with the bark lower at 0.4-0.8wt% N (DAF basis). The poplar SRF was generally higher in nitrogen than the equivalent spruce samples. While harvest time appears visually to have had little impact on levels of nitrogen in any of the spruce SRF plant parts or the poplar SRF trunk, the second harvest does generally show higher nitrogen than the first for the poplar SRF tops; this is analysed and discussed in more detail in Section 8.2.2. Levels of nitrogen in the *Miscanthus* were similar to those of the spruce SRF tops and bark.

Figure 4-6: Comparison of nitrogen (d) values across all feedstocks in study 1 & 2



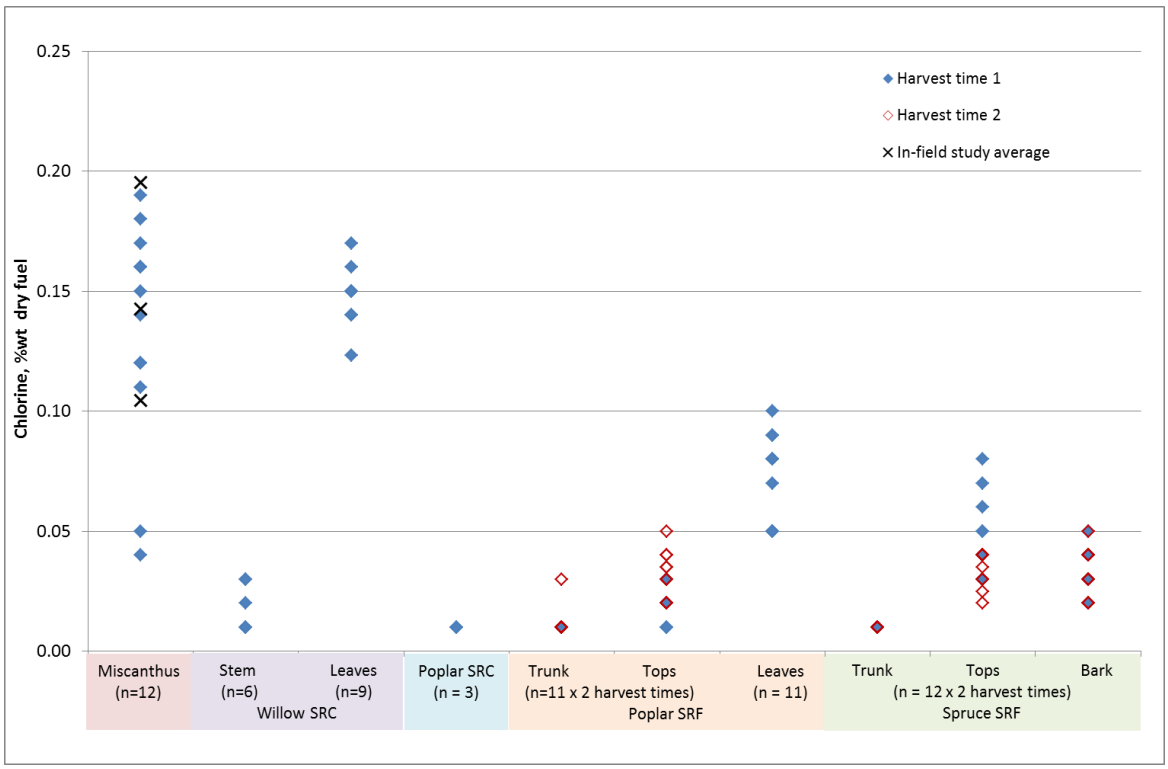
For sulphur, the leaves were again shown to contain the highest levels (up to 0.6% dry) – see Figure 4-7, with the remaining feedstocks and plant parts generally containing <0.1% (dry), although the trunks always contained the lowest levels (the trunk samples being at or below the limit of detection of 0.01%). Should leaves be combusted as a dedicated fuel, this level of sulphur may require flue gas abatement measures to be taken. However, the scenario of 100% leaf firing is considered to be unlikely as the high levels of other chemical constituents of the fuel would have multiple negative impacts on conversion plant. As with nitrogen, a particularly notable impact of harvest time on sulphur content is apparent for the poplar SRF tops; in this case this difference also seemed to be present for the spruce SRF tops to some extent. The reason for this is unclear, but may be related to differing levels of dormancy in the harvested materials, with the biggest differences seen in the more actively growing plant parts.

Figure 4-7: Comparison of sulphur (d) values across all feedstocks in study 1 & 2



For chlorine, the *Miscanthus* clearly contained the highest levels (see Figure 4-8), while the wide spread of the data for this feedstock are also notable; this is discussed further in Section 5. The Willow SRC leaves contained markedly higher levels of chlorine than those from the poplar SRF leaves. The trunks generally contained chlorine levels that were lower than the limit of analytical detection of 0.01%.

Figure 4-8: Comparison of chlorine (d) values across all feedstocks in study 1 & 2



For the most part, the overall carbon to hydrogen ratio was reasonably consistent across all feedstocks. However, when the carbon and hydrogen contents are compared across the different feedstocks, it can be seen that distinctly different clusters can be seen, as shown in Figure 4-9 for the non-spruce feedstocks and Figure 4-10 for the spruce SRF plant parts. The *Miscanthus* has the lowest levels of carbon and hydrogen, while the Willow SRC leaves and spruce tops have the highest. The spruce SRF bark does not follow the general trend of the SRF other materials, being high in carbon but relatively low in hydrogen. In these figures, harvest time is also differentiated, and for the poplar tops in particular it is clear that the second harvest shows higher carbon contents than the first, indicating the presence of leaves within the sample.

Figure 4-9: Carbon verses Hydrogen content for the non-SRF spruce feedstocks

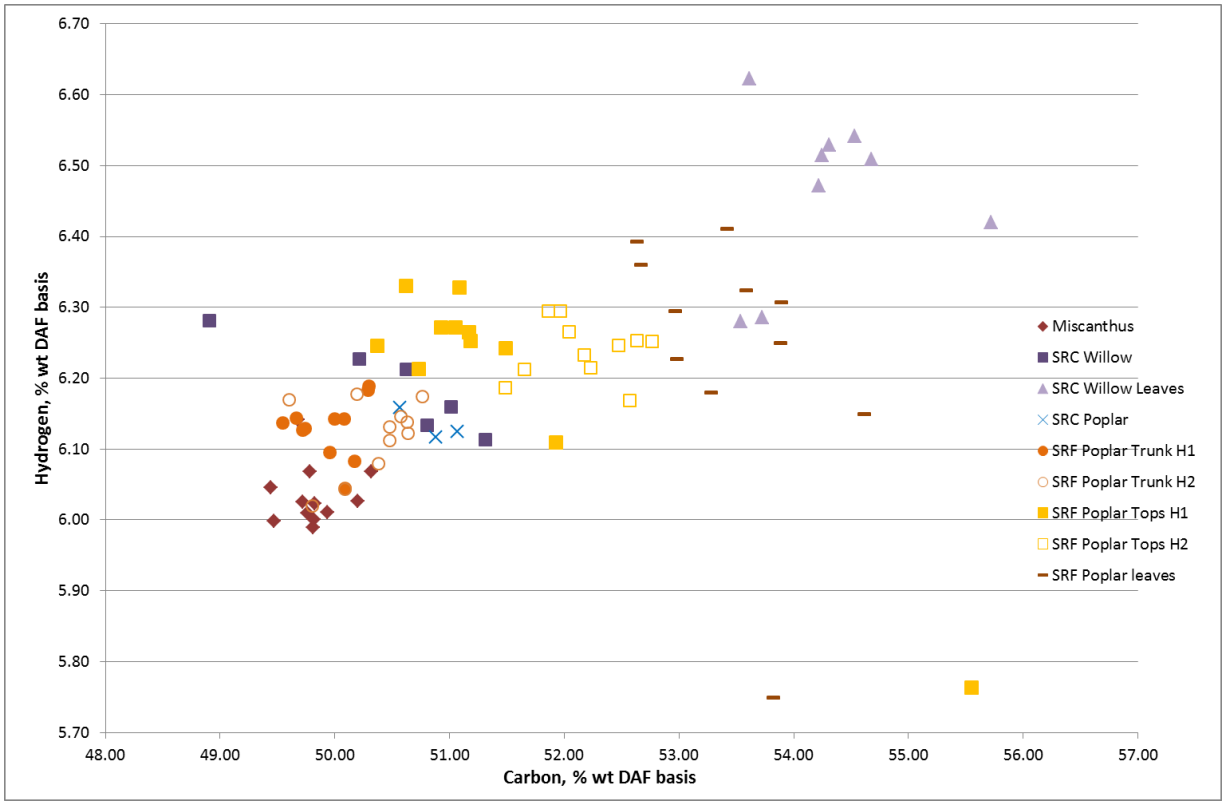
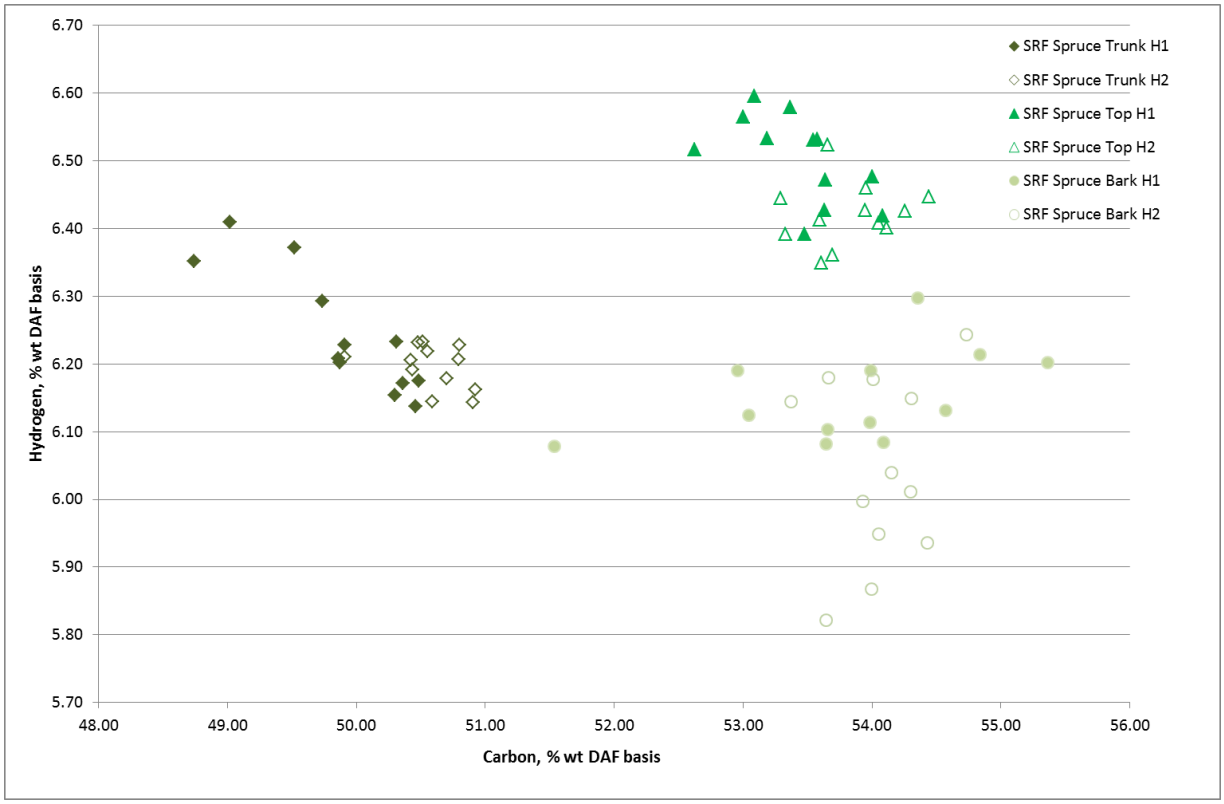


Figure 4-10: Carbon verses Hydrogen content for the SRF spruce feedstocks



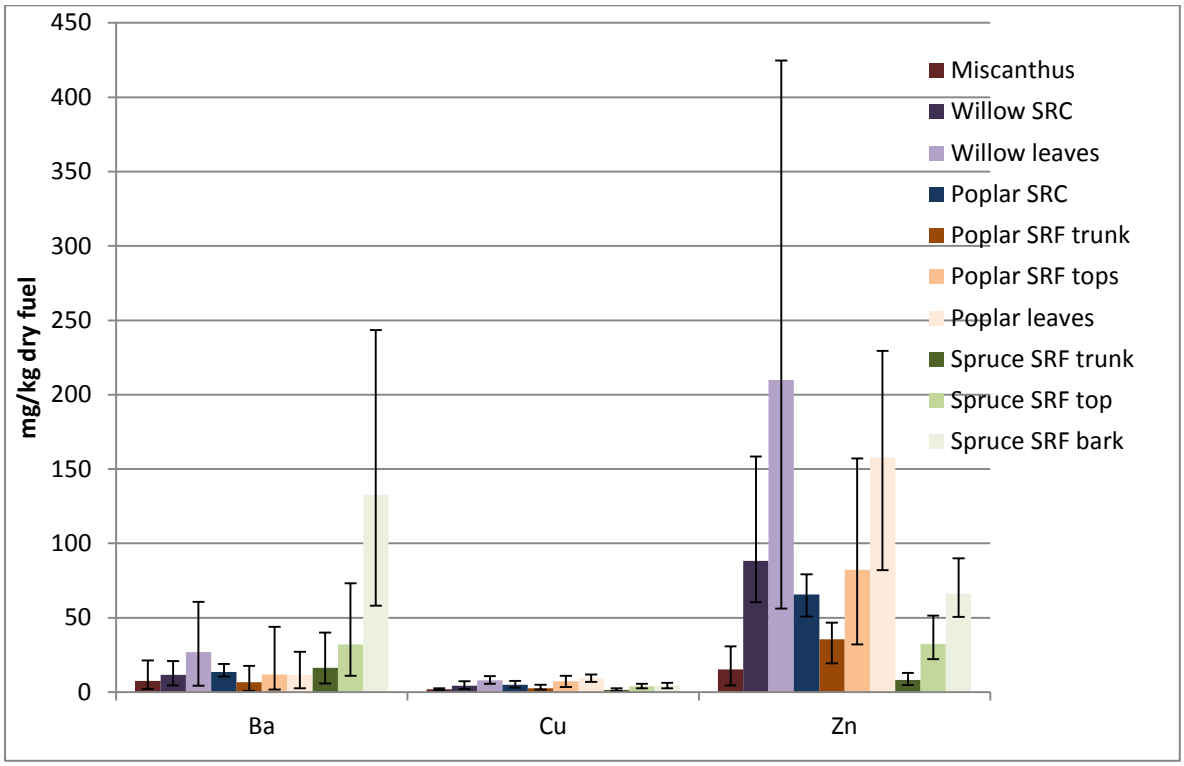
4.1.3 Trace elements

Trace and minor elements are mainly of environmental interest to the end user of fuels, both considering atmospheric emissions as well as potential impacts on ash chemistry and aqueous discharges. There is however increasing evidence that some trace metals, such as lead and zinc, may participate in corrosion mechanisms, particularly in association with chlorine. This is generally considered to be an issue that primarily affects conversion plant using waste wood as part of their feedstock (which can be significantly enriched in these metals through contamination), but may also be of concern for certain "clean" feedstocks.

Figure 4-11 to Figure 4-14 show the average trace element contents of the fresh feedstocks (harvest time is not differentiated in these graphs for clarity), with the range of the data indicated by the error bars on each column. Note that those values deemed to be outliers for statistical analysis have been excluded from these graphs to avoid distortion of the averages. For a number of the trace metals, the majority of data for some feedstocks was below or close to the analytical detection limits (note these varied by element due to different analytical techniques, with slight differences between individual samples due to the impact of differing ash content). These can generally be identified in the graphs by the low range of the data.

Generally, for the trace and minor elements, within the woody feedstock types the trunks contain the lowest levels followed by increasing concentrations in the tops and finally the leaves. For the majority of elements the SRF bark contains similar concentrations to the tops. However there are notable exceptions as discussed below each chart.

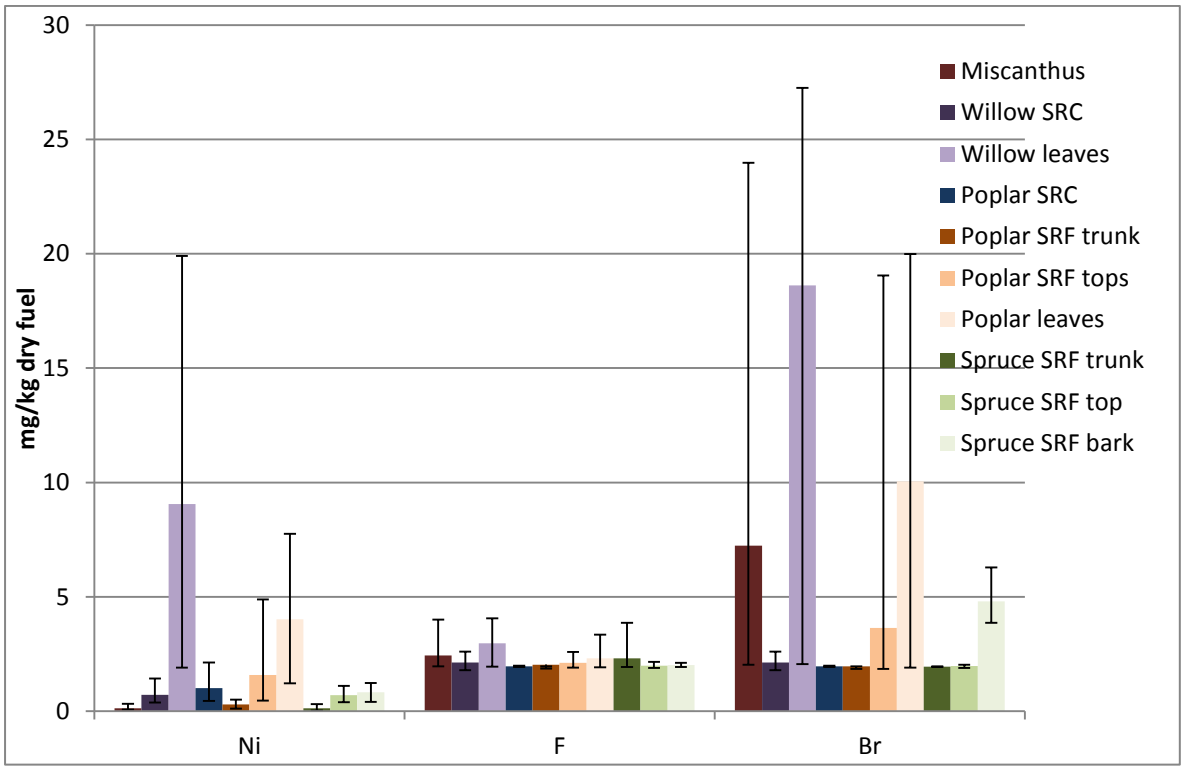
Figure 4-11: Comparison of average barium, copper and zinc values across all feedstocks in study 1 (data range indicated by error bars)



Barium – significantly higher and more variable in SRF bark than any other feedstock. Barium is not considered to have a significant impact on conversion plant.

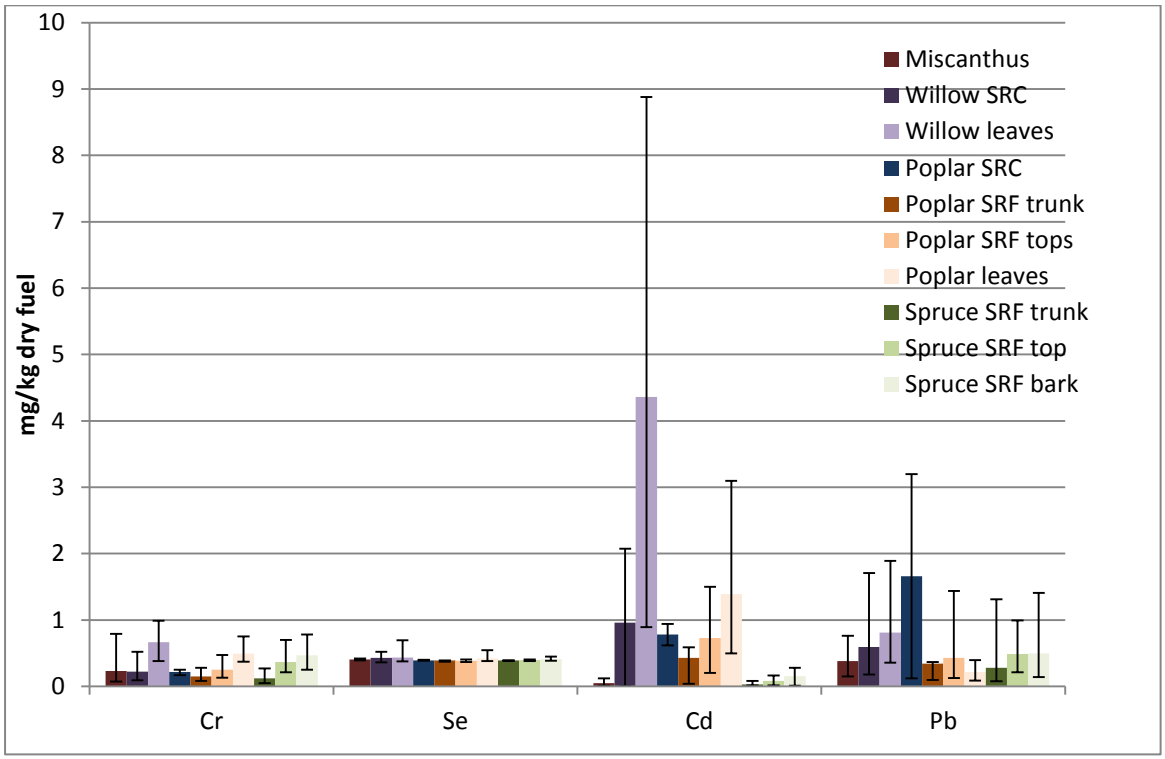
Zinc – average levels in the leaves were higher than those in the other feedstocks and the willow leaves in particular showed a wide range of concentrations; levels were also reasonably high in the SRC crops and poplar tops, although *Miscanthus* was comparatively low in zinc. Zinc concentrations are often specifically limited in boiler contracts, particularly those for waste wood combustion, as it is associated with corrosion mechanisms, especially in combination with chlorine. The levels in the leaves are comparable to those seen in some waste woods. High levels of zinc in the residual ash may also be a concern from an ecotoxic perspective.

Figure 4-12: Comparison of average nickel, fluorine and bromine values across all feedstocks in study 1 (data range indicated by error bars)



Bromine – for most of the samples tested, bromine levels were below the limit of detection However, detectable levels were found in several of the samples of *Miscanthus*, both willow and poplar leaves and one of the poplar SRF top samples, and the range of these values was quite high. All of the spruce SRF bark samples had elevated bromine levels. Bromine has been linked to corrosion mechanisms and the deterioration of baghouse filters (used for particulate matter capture).

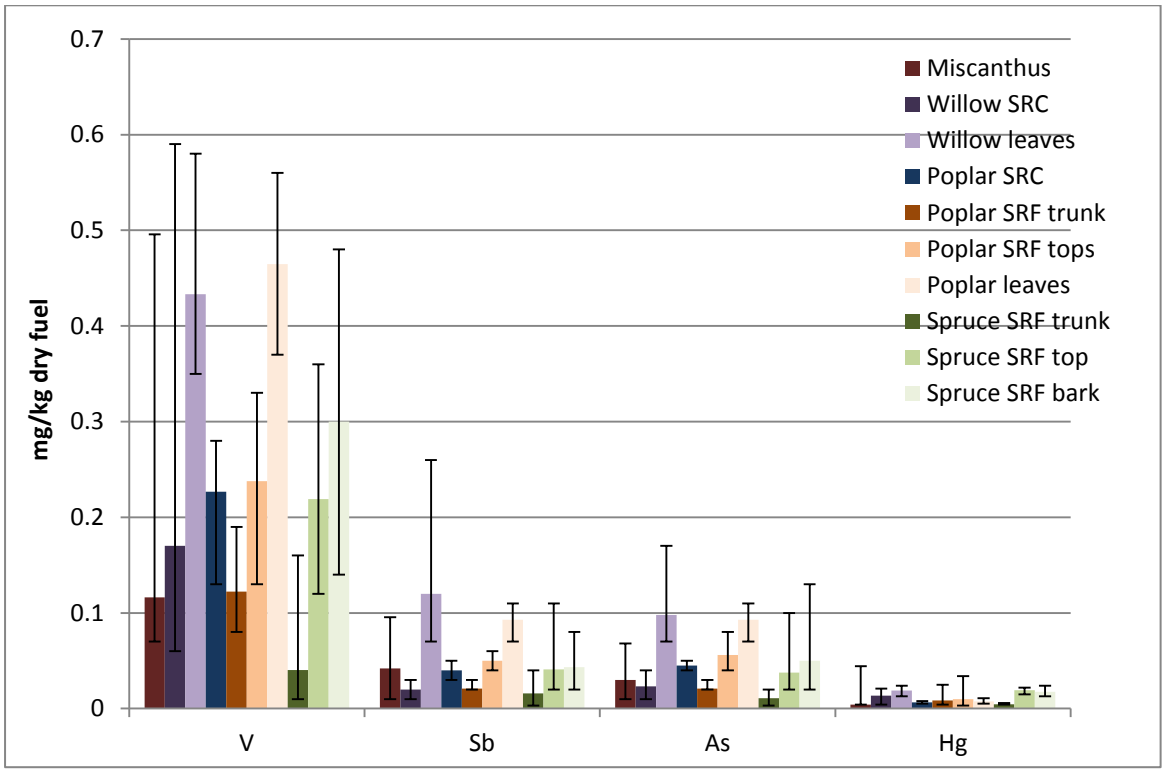
Figure 4-13: Comparison of average chromium, selenium, cadmium and lead values across all feedstocks in study 1 (data range indicated by error bars)



Cadmium – Levels in the willow leaves in particular were high and variable (comparable to those in some waste woods). All of the broadleaf samples were higher in cadmium than either the spruce or *Miscanthus* samples. Cadmium is primarily of concern as an environmental pollutant.

Lead – while the poplar SRC appears to be higher in lead than the other feedstocks, this is due primarily to one high result distorting the average due to the small number of samples. Lead levels in the other feedstocks were broadly similar. Lead is of concern both from an environmental perspective and as it is implicated in some corrosion mechanisms, but the levels seen in the feedstocks in this study are comparatively low. High levels of lead in the residual ash may also be a concern from an ecotoxic perspective, while boiler deposits containing lead could be an occupational health concern for maintenance workers.

Figure 4-14: Comparison of average vanadium, antimony, arsenic and mercury values across all feedstocks in study 1 & 3 (data range indicated by error bars)



Vanadium – many of the feedstocks showed variable vanadium concentrations, although on average the general pattern of leaves>tops>trunk is followed. Vanadium is of environmental concern but the levels in these feedstocks are low.

Mercury – many of the samples were below or close to the limit of detection. However, all the leaves and a number of the tops samples (both poplar and spruce SRF) did contain measureable levels. Mercury is of significant environmental concern and is likely to be further regulated in the near future, although the levels in these feedstocks are unlikely to require specific controls to be applied.

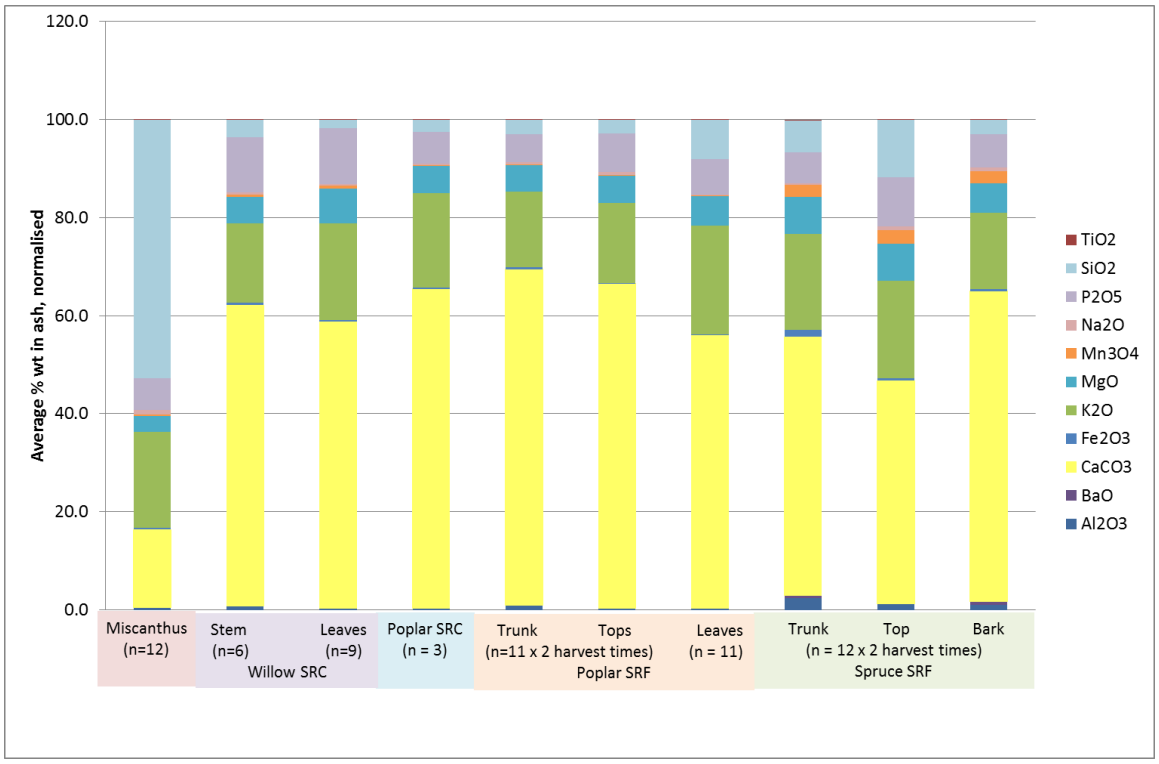
4.1.4 Ash compositions

The average ash composition for each feedstock is shown in Figure 4-15. These compositions exclude SO_3 and have been normalised to sum to 100%, with the majority of the elements expressed as oxides; the exception is calcium which is expressed as carbonate. It should be noted that these values reflect their proportions in the ash – levels of the ash forming elements in the fuel will depend on its ash percentage. The ash composition will influence a number of operational concerns within the plant, including slagging, fouling, corrosion, erosion, bed agglomeration in fluidised bed systems, emissions (particularly of acidic gases) and ash disposal/recovery options.

With the exception of the *Miscanthus*, all of the feedstock ashes were predominantly composed of calcium carbonate, with potassium oxide levels also high. High alkali input is linked to corrosion, slagging and bed agglomeration in combustion plant. Calcium can be beneficial in the reduction of acid gases, but depending on its concentration and the levels of other ash constituents it can have mixed impacts with regards to slagging and fouling.

The *Miscanthus* also contained significant levels of silica. In some cases this may be due to contamination by soil, but as the silica was consistently high, it is also likely to be an inherent characteristic of the *Miscanthus*. Silica in combination with potassium can form low melting point (eutectic) mixtures which can lead to a higher probability of slagging/fouling/ agglomeration issues.

Figure 4-15: Average normalised ash compositions for the feedstocks in study 1 & 3

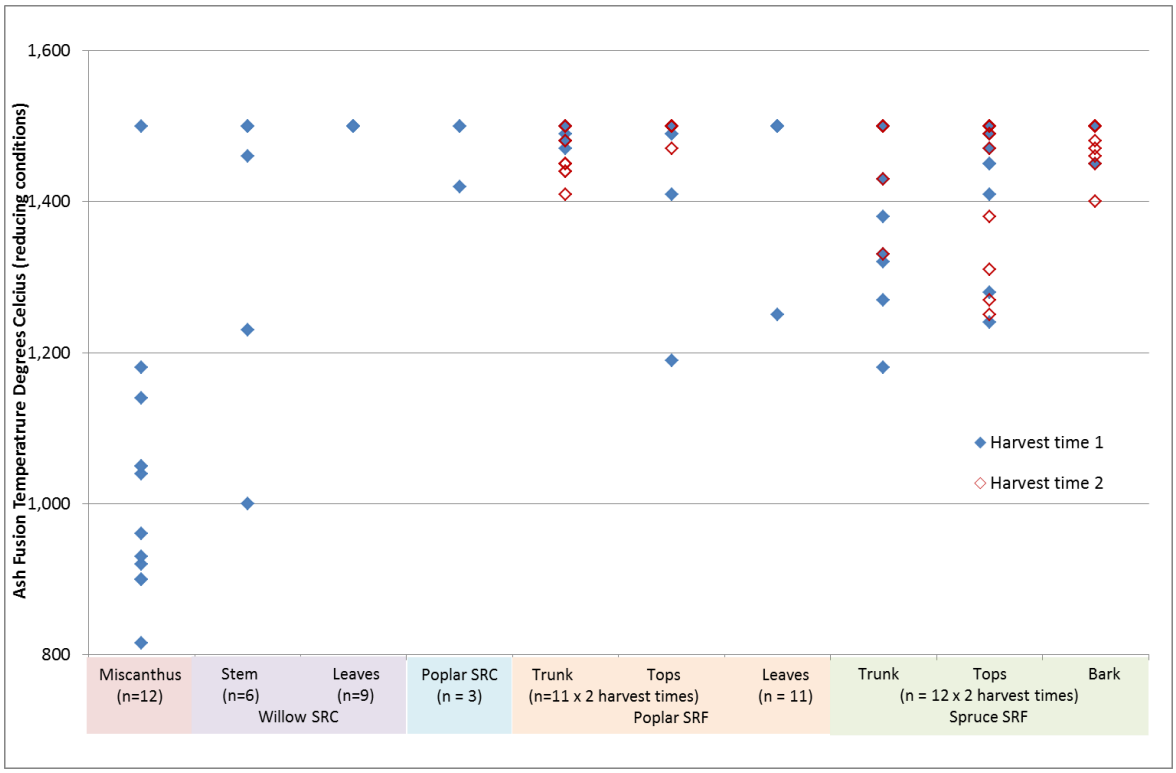


4.1.5 Ash fusion temperatures

The initial ash deformation temperatures (IDT) (under reducing conditions) for the feedstocks (not including in-field variation samples and stored material) are shown in Figure 4-16. Low ash fusion temperatures (AFTs) suggest that the ash is likely to form molten/sticky deposits in the boiler and so increase the risk of slagging and fouling. It should be noted that the reliability of AFTs is affected by a number of factors; the repeatability given in the standards is quite wide, the measurement can be dependent on operator interpretation and it can be affected by the ash preparation method. Unlike the other fuel characteristics evaluated, ash fusion temperatures (AFTs) are not considered suitable for statistical analysis, as the use of e.g. average values can hide potential issues with low melting point supplies.

The *Miscanthus* in particular had some very low IDTs but also a very wide range in values (although it is suspected that the values at >1500°C may be an error as they are so much higher than the other data). This would limit its use in many conversion systems as the risk of forming slagging deposits would be high. The woody biomass samples all had IDTs above 1000°C, with the vast majority above 1200°C, hence reducing the potential issues significantly. The willow SRC data also show a wide spread of values, however it should be noted that there were only 6 fresh samples and of these three had IDTs ≥1500°C (as did the four stored samples). The ash compositions of the willow SRC samples were reasonably consistent, which again makes the spread in the IDT data surprising.

Figure 4-16: Comparison of initial deformation temperatures (reducing conditions) across all feedstocks in study 1 & 3



4.2 Discussion

Comparison of all the fresh feedstock analysis in this Section has confirmed Hypotheses 1 and 2 (Section 1.3) which proposed that different feedstocks and different plant parts from those feedstocks would have different chemical compositions.

The dry ash free Gross CV varies from just over 19500 kJ/kg for the *Miscanthus* and stem wood up to nearly 22500 kJ/kg for the leaves, with the tops and bark samples also showing high DAF GCV values. This is due to the higher carbon and hydrogen, and hence lower oxygen content, of these parts of the plant. However, despite the higher DAF GCV values, the tendency for the leaves, tops and bark to have a higher moisture content and significantly increased dry ash content (particularly for the leaves), results in a much lower as received Net CV for these parts of the plant. Although the ash content of the spruce SRF bark was significantly higher than the trunk wood, it was broadly similar to that seen in the spruce SRF tops.

Dry nitrogen levels were lowest in the trunk wood, with spruce SRF notably lower than the willow SRC and poplar SRF samples. The highest levels (~10%) were seen in the leaf samples, with the tops and *Miscanthus* samples containing intermediate concentrations, the equivalent samples from spruce SRF always being lower in nitrogen than those from poplar SRF. A similar pattern was evident for dry sulphur content, with many of the trunk wood samples containing levels below the limits of detection. For dry chlorine content, *Miscanthus* contained some of the highest levels, along with the willow SRC leaves at up to 0.2%. Again, the chlorine content in many of the trunk samples was below the limit of analytical detection.

The increased ash content of the plant extremities (leaves, tops and bark) would be expected to influence the concentrations of many trace and macroelements and this is observed, with the trunks containing the lowest levels followed by increasing concentrations in the tops and finally the leaves. For the majority of elements the spruce SRF bark contains similar concentrations to the tops. However there are a number of notable exceptions including the observation of very high levels of barium in the bark. For the macroelements, calcium dominates the ash composition of most of the feedstocks with the exception of *Miscanthus*, which is dominated by silica. The concentrations of sodium, phosphorous, potassium tend to increase toward the plant extremities (trunk<tops<leaves) at the expense of calcium, but the spruce SRF bark shows the opposite behaviour, with more calcium than the trunk parts.

Generally, the results have revealed some interesting outcomes. Comparison of equivalent plant parts for the poplar and spruce SRF demonstrates that the spruce samples are nearly always lower in concentrations of most chemical species. This is consistent with the fact that the majority of sites in the public forest estate are too poor for agricultural purposes and are inherently low in nutrients yet sites are seldom fertilised. Thus the species grown on such nutrient poor sites are chosen because they are well adapted to low nutrition - Sitka spruce is an outstanding example – therefore low levels of nitrogen, sulphur and ash are quite plausible. High chlorine in Sitka spruce is usually associated with proximity to the sea; the low levels in the spruce SRF are consistent with the fact that all the sites in this project were well inland. The spruce bark was also much lower in ash content and hence a much better fuel than was expected. Although this is in line with the generally poor site nutrition, the industry view is generally that bark has high ash. There are two possible explanations for the low ash content of these bark samples: firstly great care was taken to prevent contamination with soil, and secondly the bark was much younger than the bark from trees harvested at the normal age of 40-50 year which would be expected to accumulate more atmospheric pollutants. The levels of ash, chlorine content and calculated alkali index for the *Miscanthus* samples were also interesting to compare against the other data in light of the general industry perception of this feedstock as being ‘problematic’.

When *Miscanthus* is compared to the other feedstocks, although only the leaves approach the *Miscanthus* chlorine levels, the ash content and calculated alkali index for the *Miscanthus* are broadly similar to those of the poplar and spruce SRF tops, suggesting that some commonly held perceptions regarding *Miscanthus* are perhaps not always justified, see Table 4-2.

Table 4-2: Comparison of ash, chlorine and alkali index averages for all fresh feedstocks

Feedstock	Ash %wt (d)	Chlorine % (DAF)	Alkali index (kg(Na_2O+K_2O)/GJ)
Miscanthus	2.3	0.14	0.204
Willow SRC	1.8	0.02	0.147
Willow SRC – Leaves	8.0	0.16	0.706
Poplar SRC	3.0	0.01	0.171
Poplar SRF – Trunk	1.6	0.01	0.112
Poplar SRF – Tops	4.5	0.03	0.340
Poplar SRF – Leaves	9.1	0.09	0.871
Spruce SRF - Trunk	0.4	0.01	0.038
Spruce SRF – Tops	2.4	0.04	0.195
Spruce SRF - Bark	2.3	0.04	0.158

5 *Miscanthus*

5.1 Introduction

Miscanthus is a C_4 pathway plant, meaning it is a plant with the ability to be highly efficient at photosynthesising. Because of this ability, *Miscanthus* can achieve high levels of annual productivity (even in temperate climates), in the form of roots (rhizomes), stems and leaves although only the stems and leaves are harvested annually for biomass.

Typical UK achievable yields after 3-4 years' maturity are 12 oven dry tonnes per hectare per annum (ODT/ha/yr), with low yields being 8 ODT/ha/yr and high yields being 16 ODT/ha/yr (ADAS, 2003). Yields of *Miscanthus* on mainland Europe, where the season is marginally longer, can easily achieve >18 ODT/ha/yr.

Most *Miscanthus* plantations are established at rates ranging between 10,000-25,000 rhizomes/ha. These are generally 50-100 g rhizome pieces, which will have been lifted and produced from multiplication crops no older than 5 years of age.

The growth cycle of *Miscanthus* is an annual cycle in temperate climates. This cycle would start in spring (when soil temperatures are above 6°C), and will grow steadily (approx. 2 cm per day) through the summer and start to senesce early autumn. Produced cane (biomass yield) is then over-wintered to allow shedding of the leaves to occur, as the leaves typically tend to contain higher levels of unwanted feedstock characteristics, i.e. potassium, silicon, and chlorine. The overwintering process also provides the standing cane time to reduce in moisture content.

Harvesting usually takes place from late winter onwards, when weather and ground conditions allow, with the aim of being completed before the new shoots start to appear from the ground in early spring. This is when the highest dry matter content can be achieved (approx. 80%), and where most of the nutrients have been sequestered from the upper part of the plant back down into the rhizomes – improving fuel quality aspects of the harvested cane and giving the rhizome/roots the nutrients required for starting the following growing season.

Miscanthus has hundreds of different varieties and more are being bred and developed each year. New varieties are continually being developed, aiming to improve fuel quality aspects, yield and planting efficiency (by establishing from seed/plantlet rather than rhizomes).Throughout Europe and North America, the most common *Miscanthus* variety established for commercial biomass production has been *M. x giganteus*.

M. x giganteus is a sterile hybrid, due to its triploid property, so only can be propagated from cuttings or rhizomes; all the *Miscanthus* samples collected in this project were *M. x giganteus*. The main benefits of *M. x giganteus* are:

- reasonable frost tolerance (capable of surviving -20°C air temperature with only 10% plant losses).
- good annual yield production with little annual variation
- wide range of suitable soil types and nutrient requirements
- little or no requirement for nitrogen fertiliser
- no significant recorded incident of disease infection

- very good resistance to insect pest attack
- commercially productive life span of >15 years

This project investigated the variability of *Miscanthus* in three different studies. The first study related to taking samples across twelve different sites whilst the second focussed on assessing the variability within three individual sites (in-field variation). Both of these studies are considered in this section (see Figure 5-1 for the geographical location of the relevant sites). The final study, related to the characteristics of *Miscanthus* before and after pelletising, is considered in Section 11.

Study 1 focussed on the effect of the climate zone (warm/moist, warm/dry), actual soil type (light, medium), and storage on feedstock characteristics. There were three sampling exercises on the same material to investigate the effect of storage time:

- In field at time of commercial harvest operation
- In field before collection/baling
- After baling, material was stored in either an enclosed building or open situation for 1 month (after 1 month storage)

One representative sample was analysed from each site location at each sampling time. For the fresh samples, each was formed as a composite of subsamples taken from at least 10 locations within the site, before being bulked, thoroughly mixed, and sampled for analysis.

Because of the sampling design, this study also allowed the interactions between these factors to be investigated, for example the response to storage could be different in warm/moist climate zones compared to warm/dry climate zones.

To investigate the importance of these factors, the original design intended that there were three sites in each combination of climate zone and soil type. A set of twelve sites was identified by GIS, but for reasons described in Section 2.4, the representation was not balanced, with ten sites in warm/dry climate zones and only two in warm/moist zones and more on light soils than medium soils (see Table 5-1). The outcomes from this structured analysis are presented in Section 5.2.

Table 5-1: Numbers of sites sampled in different combinations of soil type, climate zone and storage

Storage	Climate Zone	Soil Type	
		Light	Medium
Infield at harvest	Warm/dry	7	3
	Warm/moist	1	1
Infield pre-baling	Warm/dry	6*	2*
	Warm/moist	1	0*
After 1 month storage	Warm/dry	7	3
	Warm/moist	1	1

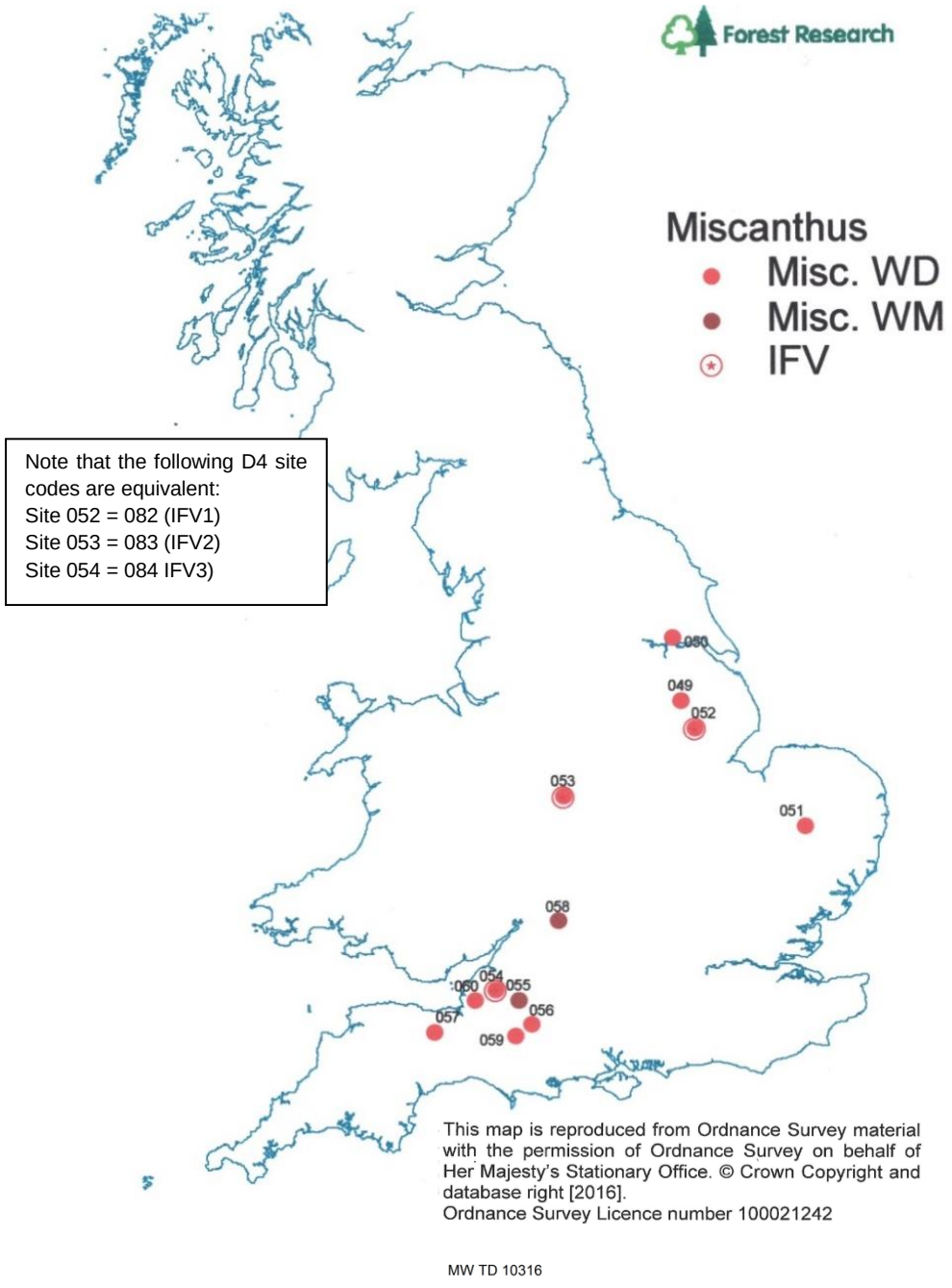
*some sites were baled as soon as they were harvested

Further information on many aspects of each of the twelve sites was collected for the purpose of understanding reasons for any observed differences in the feedstock characteristics. The provenance information included management factors as discussed in Section 3.2.

Study 2 investigated the variation within sites, also referred to as 'in-field variation'. Three sites were chosen for this and at each site, 20 biomass samples were collected and analysed separately which allowed the variability within each field to be investigated. These data were also compared to the variability between different sites. The results are presented in Section 5.5.

Figure 5-1 shows the geographical location of the *Miscanthus* sites sampled in Study 1 and Study 2.

Figure 5-1: Location of *Miscanthus* sampling sites (WD = warm/dry climate, WM = warm/moist climate, IFV = in-field variation sampling). Location numbers reference site codes used in D4.



5.2 Results of structured analysis of the effect of climate zone, soil type and storage on feedstock characteristics

Table 5-2 provides an overview of the impact of the three main experimental factors (structured factors) - climate zone (CZ), soil type (ST) and storage (STORE) - on each of the measured feedstock parameters. The table gives the probability of the observed values happening by chance alone for each of the selected feedstock characteristics. The columns CZ & ST, CZ & STORE and ST & STORE show the effect of the interactions of each of the pairs of factors whilst column CZ & ST & STORE illustrates the effect of the interactions of all three. In Table 5-2, the closer the value is to zero, then the greater the influence of the structured factor on the parameter in question. The cells have been coloured light blue to highlight those with $p<0.05$ and >0.001, i.e. there was a probability of between 1 in 20 and 1 in 1000 that the effect was due to chance alone, whilst dark blue indicates those influenced most ($p<0.001$, i.e. there was a probability of less than 1 in 1000 that the effect was due to chance alone). Note that these conventions are used throughout for the other feedstocks analysed as part of Study 1; similarly the abbreviations used for the basis of the feedstock analysis (as received = (ar), dry = (d), dry, ash-free = DAF) normalised ash = (na)) are used consistently throughout each feedstock section.

Before describing the statistically significant effects in detail, each feedstock characteristic identified in the statistical analysis was reviewed according to the measured mean values in relation to the analytical limits of detection, its analytical error, i.e. its reproducibility, and operational significance (see Section 3.1 for further explanation). Regardless of statistical significance, all effects that were at the limit of detection, within the analytical reproducibility, or judged to have limited operational impact in conversion systems were not considered further. Table 5-3 shows how each of the feedstock characteristics were assessed; those that remained following this screening step are not only statistically significant but also analytically and operationally significant.

For *Miscanthus*, climate zone significantly influenced the greatest number of feedstock characteristics. The strongest impact of climate zone was observed on the content of $CaCO_3$ and MgO in the ash, with lesser impacts on dry ash content, DAF Gross CV, cobalt, Fe_2O_3 in ash, potassium, silicon and alkali index.

Table 5-2: Structured factor analysis of *Miscanthus*

Variable (basis of analysis)†	CZ	ST	STORE	CZ & ST	CZ & STORE	ST & STORE	CZ & ST & STORE
Moisture (ar)	0.649	0.278	0.000	0.648	0.450	0.382	0.067
Net calorific value (ar)	0.499	0.308	0.000	0.619	0.471	0.414	0.075
Ash content (d)	0.005	0.891	0.753	0.636	0.844	0.776	0.934
Volatile matter (DAF)	0.267	0.149	0.087	0.670	0.087	0.019	0.247
Gross calorific value (DAF)	0.010	0.250	0.911	0.414	0.088	0.228	0.197
Carbon (DAF)	0.074	0.816	0.013	0.185	0.307	0.896	0.026
Hydrogen (DAF)	0.361	0.538	0.003	0.655	0.321	0.424	0.149
Nitrogen (DAF)	0.557	0.010	0.123	0.083	0.450	0.385	0.404
Sulphur (DAF)	0.576	0.536	0.469	0.708	0.869	0.863	0.745
Chlorine (DAF)	0.305	0.159	0.089	0.410	0.399	0.802	0.735
Barium (d)	0.534	0.673	0.609	0.746	0.673	0.740	0.948
Chromium (d)	0.438	0.178	0.959	0.693	0.842	0.997	0.993
Cobalt (d)	0.025	0.768	0.178	0.952	0.998	0.605	0.803
Copper (d)	0.179	0.144	0.845	0.651	0.703	0.281	0.705
Molybdenum (d)	0.568	0.058	0.344	0.538	0.894	0.049	0.979
Nickel (d)	0.620	0.082	0.361	0.550	0.895	0.056	0.999
Vanadium (d)	0.541	0.676	0.146	0.002	0.000	0.823	0.681
Zinc (d)	0.084	0.121	0.377	0.564	0.998	0.989	0.833
Cadmium (d)	0.594	0.765	0.669	0.737	0.999	0.653	0.525
Lead (d)	0.849	0.517	0.550	0.755	0.920	0.539	0.880
Al_2O_3 (na)	0.722	0.871	0.339	0.596	0.374	0.792	0.616
BaO (na)	0.856	0.582	0.991	0.755	0.881	0.565	0.464
$CaCO_3$ (na)	0.000	0.314	0.824	0.347	0.306	0.739	0.395
Fe_2O_3 (na)	0.004	0.015	0.678	0.095	0.013	0.957	0.352
K_2O (na)	0.121	0.108	0.290	0.161	0.394	0.433	0.685
MgO (na)	0.000	0.000	0.642	0.127	0.221	0.821	0.288
Mn_3O_4 (na)	0.730	0.398	0.260	0.822	0.195	0.128	0.363
Na_2O (na)	0.176	0.454	0.676	0.401	0.153	0.484	0.146
P_2O_5 (na)	0.281	0.095	0.558	0.899	0.607	0.926	0.084
SiO_2 (na)	0.060	0.088	0.635	0.800	0.817	0.601	0.622
TiO_2 (na)	0.631	0.462	0.802	0.929	0.950	0.792	0.900
Aluminium (d)	0.498	0.803	0.617	0.671	0.557	0.864	0.690
Calcium (d)	0.162	0.818	0.529	0.260	0.026	0.990	0.616
Iron (d)	0.574	0.122	0.736	0.454	0.182	0.969	0.650
Potassium (d)	0.027	0.495	0.598	0.562	0.864	0.676	0.857
Magnesium (d)	0.772	0.004	0.649	0.239	0.428	0.601	0.128
Manganese (d)	0.951	0.507	0.617	0.727	0.221	0.296	1.000
Sodium (d)	0.578	0.517	0.762	0.921	0.981	0.276	0.776
Phosphorous (d)	0.242	0.006	0.983	0.371	0.932	0.912	0.536
Silicon (d)	0.022	0.156	0.936	0.485	0.869	0.930	0.967
Titanium (d)	0.410	0.538	0.765	0.919	0.996	0.802	0.857
Alkali index	0.025	0.526	0.591	0.580	0.868	0.681	0.858

†basis of analysis; ar = as received fuel, d = dry fuel, DAF = dry, ash-free fuel, na= normalised ash. * Indicates not included in structured analysis. Antimony, arsenic, mercury and bromine were not included in the structured analysis due to limits of detection. Dark blue cells indicate $p<0.001$; light blue cells $0.001<p<0.05$

Table 5-3: Mean values and assessment of relevance for main effects and interactions identified by structured analysis for *Miscanthus* (number of analyses if not default)

One factor analysis				
Variable	Storage			Assessment
	Fresh	Before baling	One month stored	
Default number of analyses	12	9	12	
Moisture, %wt (ar)	26.5	14.8	13.9	Relevant for further study
NCV kJ/kg (ar)	12531	14889	15085	Relevant for further study
C, %wt (DAF)	49.81	49.66	49.36	Exclude – within repeatability of analysis
H, %wt (DAF)	6.04	6.09	6.15	Exclude – within repeatability of analysis
	Climate zone			
	Warm/dry	Warm/moist		
Default number of analyses	28	5		
Ash, %wt (d)	2.4	1.5		Relevant for further study
GCV, kJ/kg (DAF)	19639	19745		Exclude – within repeatability of analysis
Co, mg/kg (d)	0.13	0.07		Exclude – at or below limit of detection level
$CaCO_3$, %wt (na)	14.31	27.51		Relevant for further study
Fe_2O_3, %wt (na)	0.33	0.65		Unlikely to have operational impact
MgO, %wt (na)	2.82	4.38		Relevant for further study
K, mg/kg (d)	3162	1481		Relevant for further study
Si, mg/kg (d)	5446	3014		Relevant for further study
Alkali Index	0.207	0.099		Relevant for further study
	Soil Type			
	Light	Medium		
Default number of analyses	23	10		
Nitrogen, %wt (DAF)	0.39	0.32		Exclude – within repeatability of analysis
Fe_2O_3, %wt (na)	0.44	0.25		Unlikely to have operational impact
MgO, %wt (na)	3.48	2.07		Relevant for further study
Mg, mg/kg (d)	368	242		Relevant for further study
P, mg/kg (d)	439.9	621.8		Relevant for further study

Two factor analysis				
Parameter	Climate zone / Soil type	Warm/dry	Warm/ moist	Assessment
V, mg/kg (d)	Light	0.14 (18)	0.22 (3)	Exclude – within repeatability of analysis and unlikely to have operational impact
	Medium	0.16 (8)	0.08 (2)	

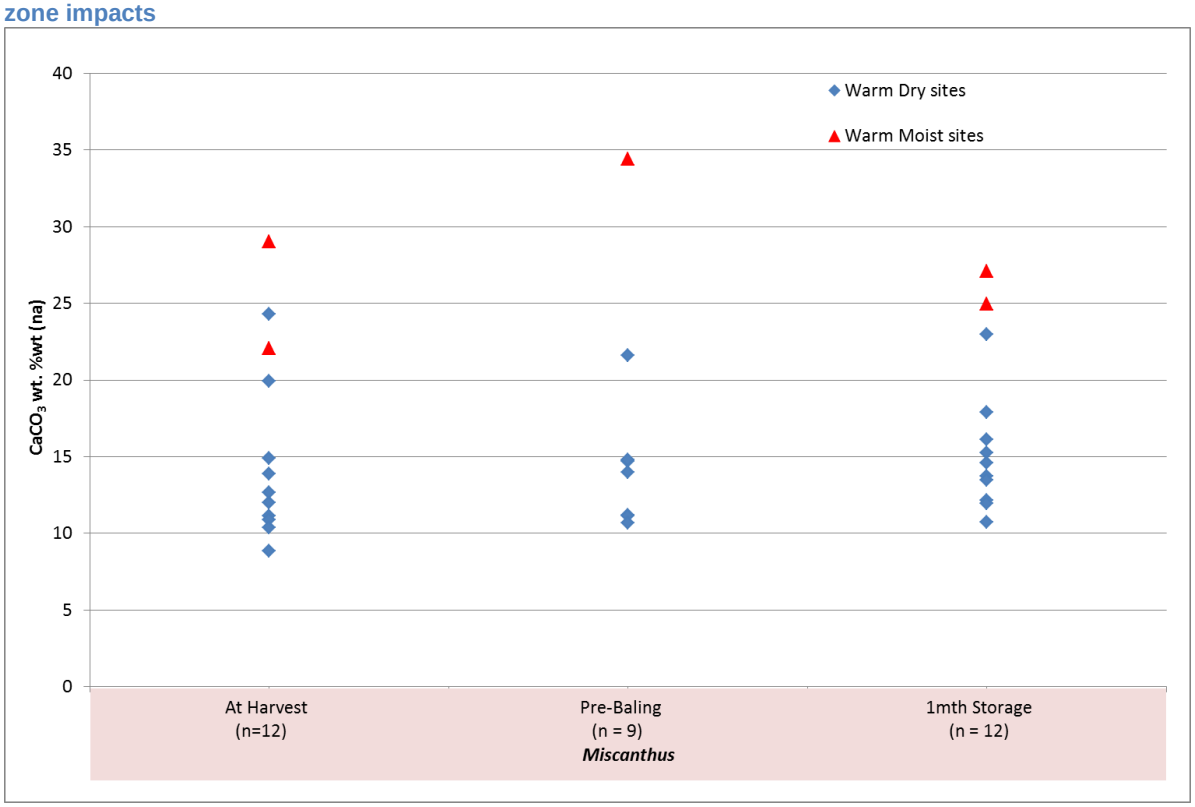
Parameter	Climate zone / Storage	Warm/dry	Warm/ moist	Assessment
V, mg/kg (d)	Fresh	0.12 (9)	0.08 (2)	Exclude – within repeatability of analysis and unlikely to have operational impact
	Before baling	0.13 (8)	0.51 (1)	
	Stored	0.18 (9)	0.07 (2)	
Fe_2O_3, %wt (na)	Fresh	0.28 (10)	0.45 (2)	Exclude – within repeatability of analysis
	Before baling	0.27 (8)	1.6 (1)	Single high sample in warm moist climate zone
	Stored	0.42 (9)	0.37 (2)	Exclude – within repeatability of analysis
Ca, mg/kg	Fresh	1096 (10)	1304 (2)	Unlikely to have operational impact
	Before baling	1169 (8)	2658 (1)	Single high sample in warm moist climate zone
	Stored	1166 (10)	1322 (2)	Unlikely to have operational impact
Parameter	Soil Type / Storage	Light	Medium	Assessment
Volatile Matter, % (DAF)	Fresh	82.2 (8)	83.8 (4)	Exclude – within repeatability of analysis and unlikely to have operational impact
	Before baling	82.4 (7)	84.8 (2)	
	Stored	83.2 (8)	83.6 (4)	
Mo, mg/kg (d)	Fresh	0.18 (8)	0.27 (4)	Exclude – within repeatability of analysis and unlikely to have operational impact
	Before baling	0.19 (7)	9.71 (2)	
	Stored	0.16 (8)	0.28 (4)	

Three factor analysis

Parameter	Climate zone / Soil Type / Storage	Warm/dry		Warm/moist		Assessment
		Light	Medium	Light	Medium	
Carbon, %wt (DAF)	Fresh	49.83 (7)	49.74 (3)	49.94 (1)	49.82 (1)	Exclude – within repeatability of analysis
	Before baling	49.64 (6)	49.61 (2)	49.83 (1)	* (0)	
	Stored	49.32 (7)	49.04 (3)	49.44 (1)	50.49 (1)	

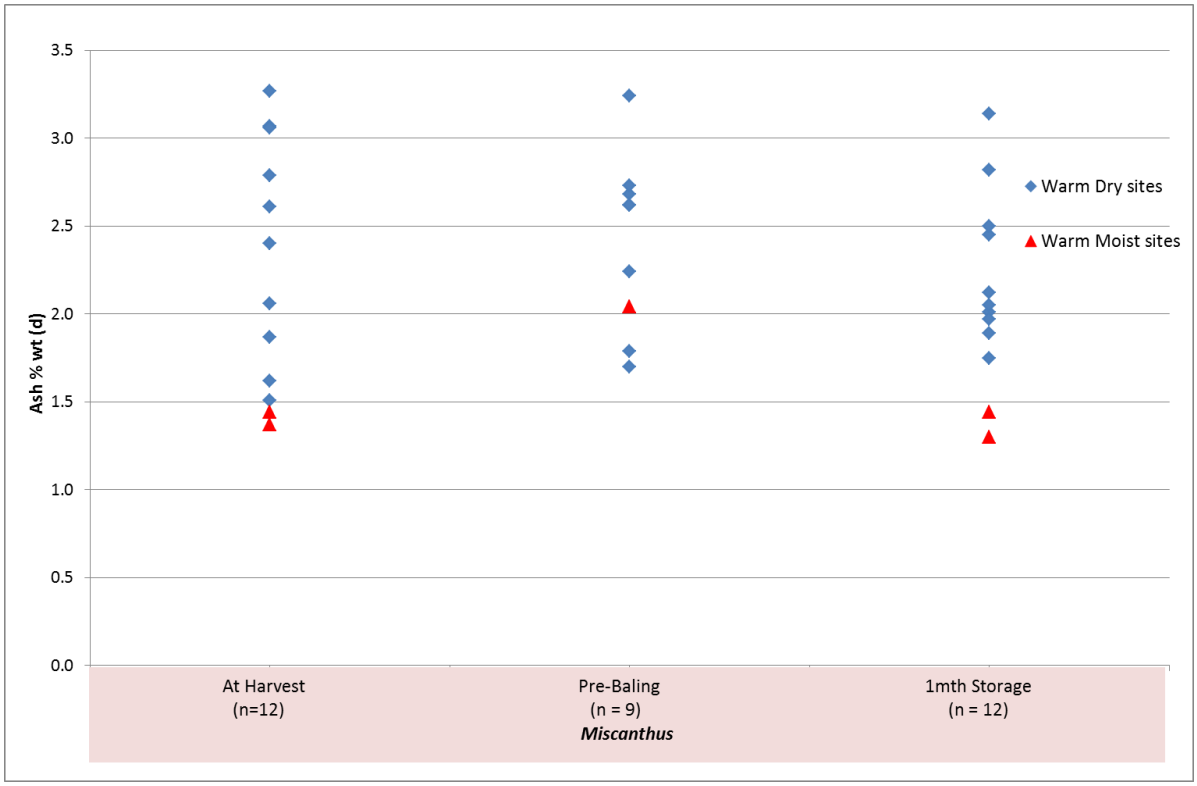
The changes in concentration of $CaCO_3$ and MgO in ash are judged to be significant (27.5% cf. 14.3% and 4.38% cf. 2.82% respectively for warm/moist and warm/dry climate zones). Figure 5-2 illustrates the changes in $CaCO_3$ in ash with climate zone, although the graph highlights the relative lack of data from warm/moist sites (five values from two sites) compared to the warm/dry sites (28 values from 10 sites).

Figure 5-2: Results from the calcium carbonate in ash analysis of *Miscanthus* in study 1, showing climate zone impacts



Likewise, the increases in dry ash content, potassium and silicon in the fuel are also judged to be significant on moving from warm/moist to a warm/dry climate zone. Figure 5-3 illustrates the change in dry ash content between the two climate zones.

Figure 5-3: Results from the ash analysis of *Miscanthus* in study 1, showing climate zone impacts

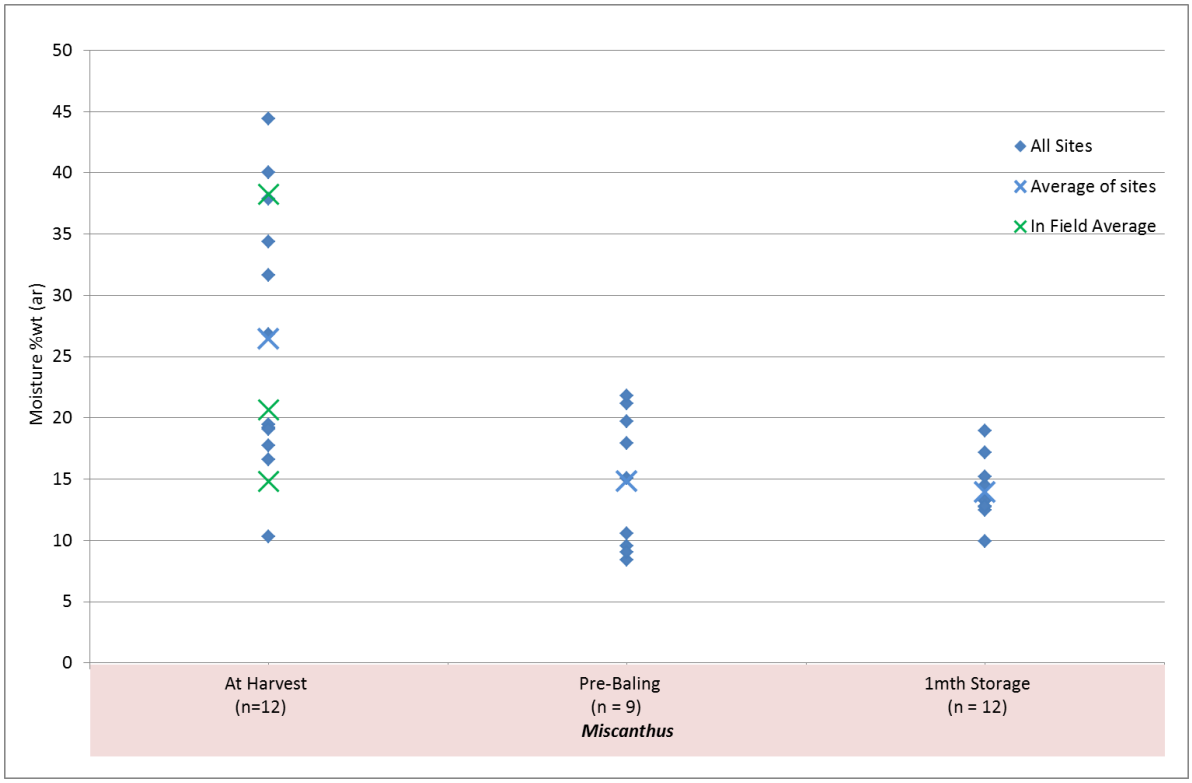


For the other parameters, the differences in DAF GCV between the different climate zones were within the analytical repeatability of the experiment, and for cobalt virtually every result was determined at below the limit of detection. Likewise, for the impact on Fe_2O_3 content in ash, the observed increase is primarily due to a single high result in one of just five samples.

The structured analysis identified that soil type impacted most strongly on MgO content in ash, with a lesser impact on dry nitrogen content, Fe_2O_3 in ash, and finally magnesium and phosphorous expressed as elements in the fuel. The change in nitrogen content is judged to be close to analytical repeatability, so can be disregarded.

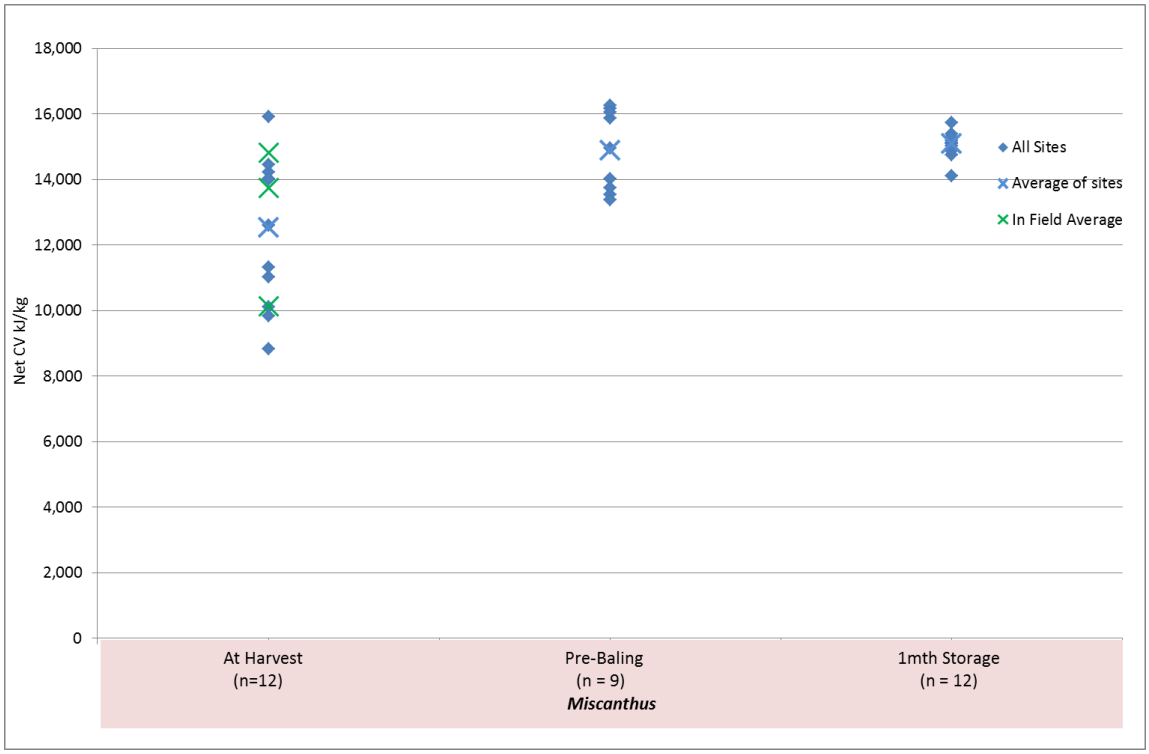
Storage would be expected to have a significant impact on moisture content in particular and the statistics confirm this hypothesis. The change in moisture content has a consequential effect on all the parameters reported on an 'as received' basis, noting that NCV is directly correlated (inversely) with moisture in any case *via* its calculation from GCV. The statistics also highlighted a lesser impact on DAF carbon and DAF hydrogen. Figure 5-4 below illustrates the reduction in moisture content of the *Miscanthus* from each of the 12 sites (including the average value from the study 1 sites); the average moisture content determined from each of the three in-field variation sites (study 2) is also included.

Figure 5-4: Results from the moisture analysis of *Miscanthus*



The reductions in moisture content on storage were substantial, particularly the drying that occurs in the field after harvesting, but prior to baling, as were the consequent increases in NCV, as shown in Figure 5-5.

Figure 5-5: Results from the Net Calorific Value analysis of *Miscanthus*



Clearly, the extent of drying will be strongly influenced by available surface area of the material, which will be different pre- and post-baling and dependent on the climatic conditions during storage. The *Miscanthus* bales were generally stored undercover for these experiments, and more information on the impacts of different methods of storage will be assessed in Phase 2 of this project, specifically variation 4. The differences in DAF carbon and hydrogen were not significant given the analytical repeatability. Perhaps most importantly, the statistical analysis suggested that storage did not have any impact on the levels of any of the trace elements or macroelements, including nitrogen and chlorine - Figure 5-6 and Figure 5-7 demonstrate the relatively consistent levels of both nitrogen and chlorine in the samples taken at harvest and the two storage conditions. Unless any of the trace elements are either leached or lost through vaporisation (chemical reaction – heating, followed by decomposition) whilst in storage, then in theory any changes in element levels should be insignificant during storage, assuming storage conditions and method used are suitable for the feedstock being stored.

Figure 5-6: Results from the nitrogen analysis of *Miscanthus*

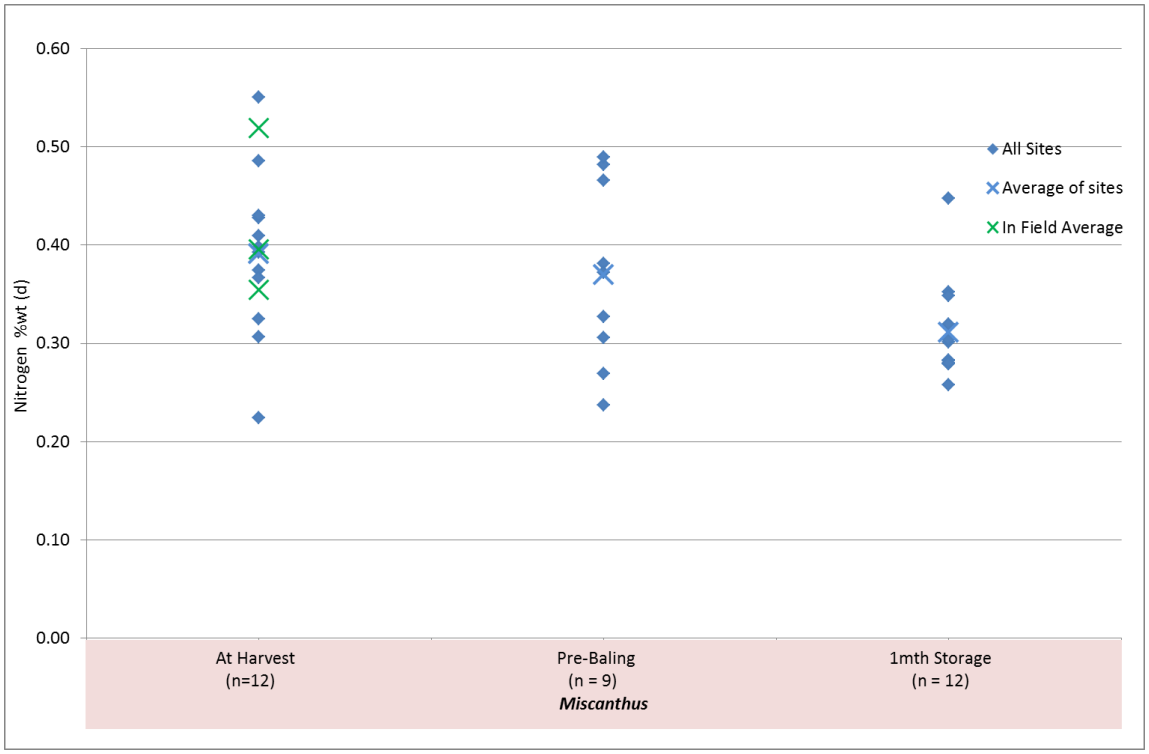
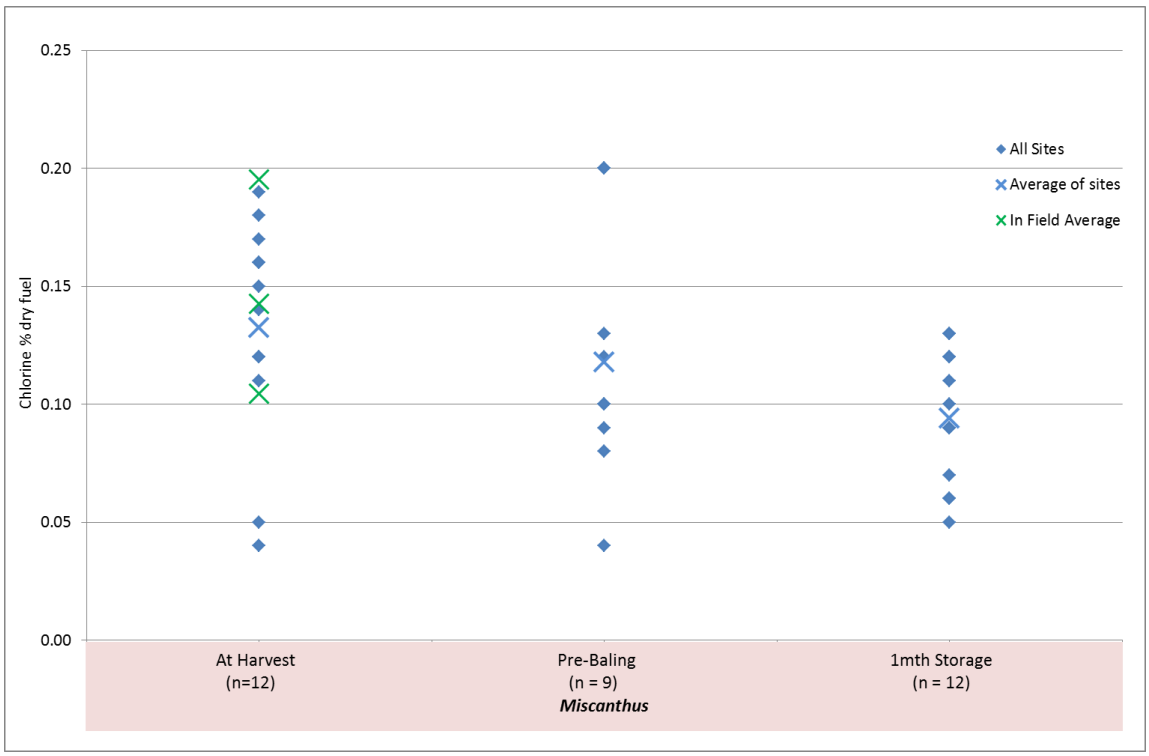


Figure 5-7: Results from the chlorine analysis of *Miscanthus*



In the vast majority of cases the three structured factors (storage, climate zone and soil type) did not interact significantly. The statistical analysis did highlight significant impacts of a few interactions, but closer inspection of the data reveals that for all but the characteristics previously discussed, the majority of the data was either at the limit of detection or within analytical repeatability (Table 5-3). In addition, the lack of samples from the warm/moist climate zone meant that for certain combinations only a single sample was available.

Visual examination of the graphs also suggests a possible benefit in the levels of chlorine, which appear to reduce marginally between harvesting time and collection/baling time (Figure 5-7), although this was not highlighted by the statistics. Further graphs for the other feedstock parameters are provided in Appendix 8.

5.3 Null hypothesis

Of the many site properties collected for *Miscanthus*, the following had sufficient variation in the data to be suitable for statistical analysis: year of planting, soil classification, pH and cation exchange capacity (CEC). The impact of soil classification was investigated in the structured analysis (Section 5.2), while the impact of pH and CEC are covered in the correlation analysis, which is presented in Section 5.4. Therefore only year of planting is examined here.

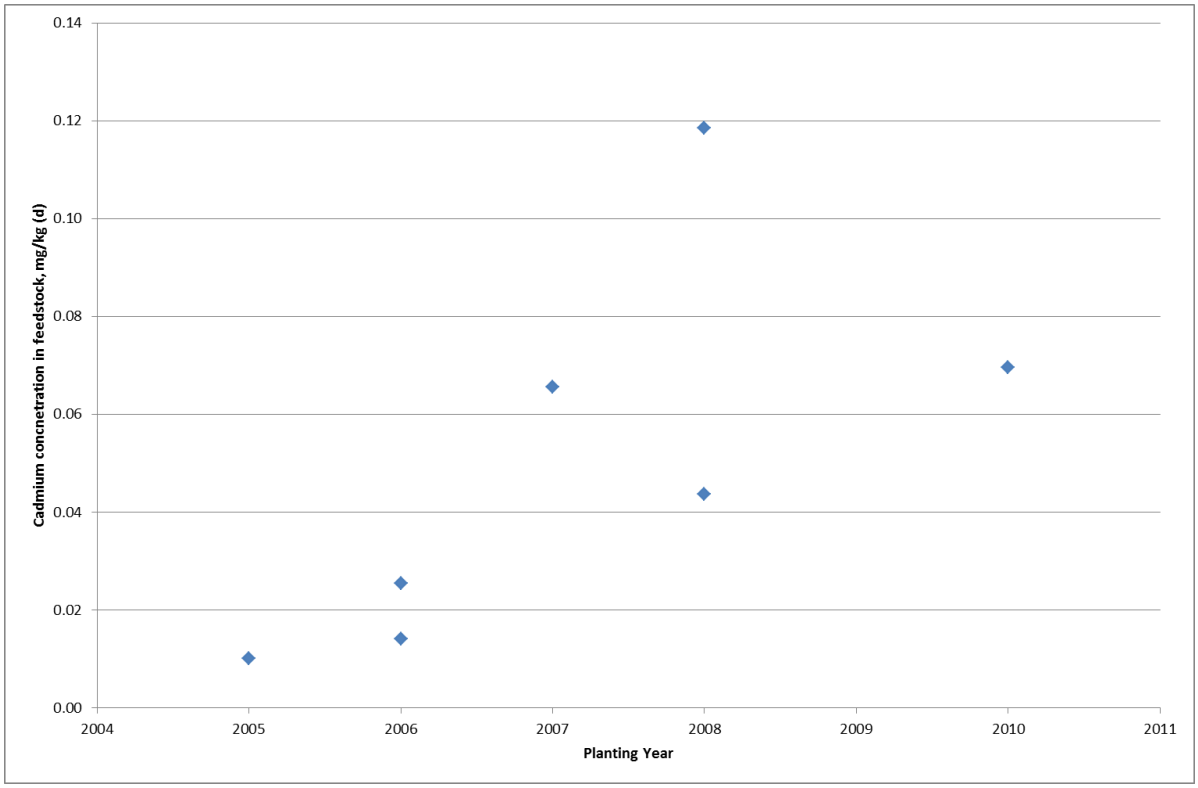
As discussed in Section 2.6.3, correlation analysis was undertaken between the year of planting and the feedstock characteristics. The full results of this analysis are presented in Appendix 9, with these tables colour-coded to indicate those correlations (positive or negative) which explain either >50% or >80% of the variability, as discussed in Section 2.6.5. Table 5-4 presents an extract of this table, showing the strongest correlations.

Table 5-4: Regressions between selected provenance information and feedstock characteristics of fresh *Miscanthus*

Variable (basis)	Correlation with Year of planting
Antimony (d)	0.921
Arsenic (d)	0.763
Mercury (d)	-0.726
Cadmium (d)	0.873

Year of planting was closely correlated with a small group of trace element concentrations in the feedstock (Sb, As, Cd and Hg), but with the exception of cadmium, the concentrations of these elements were at or below the limit of detection and so the data are unreliable. For cadmium, few of the analyses were below the limit of detection, allowing further exploration; a positive correlation was found, indicating that the concentrations increased in *Miscanthus* crops with later planting dates (i.e. less mature crops), as shown in Figure 5-8. This could be due to physiological differences in younger crops. Alternatively, this may be due to changes in management practices that were not captured in the collected provenance data.

Figure 5-8: Correlation between year of planting and cadmium levels in fresh *Miscanthus*



5.4 Determining factors

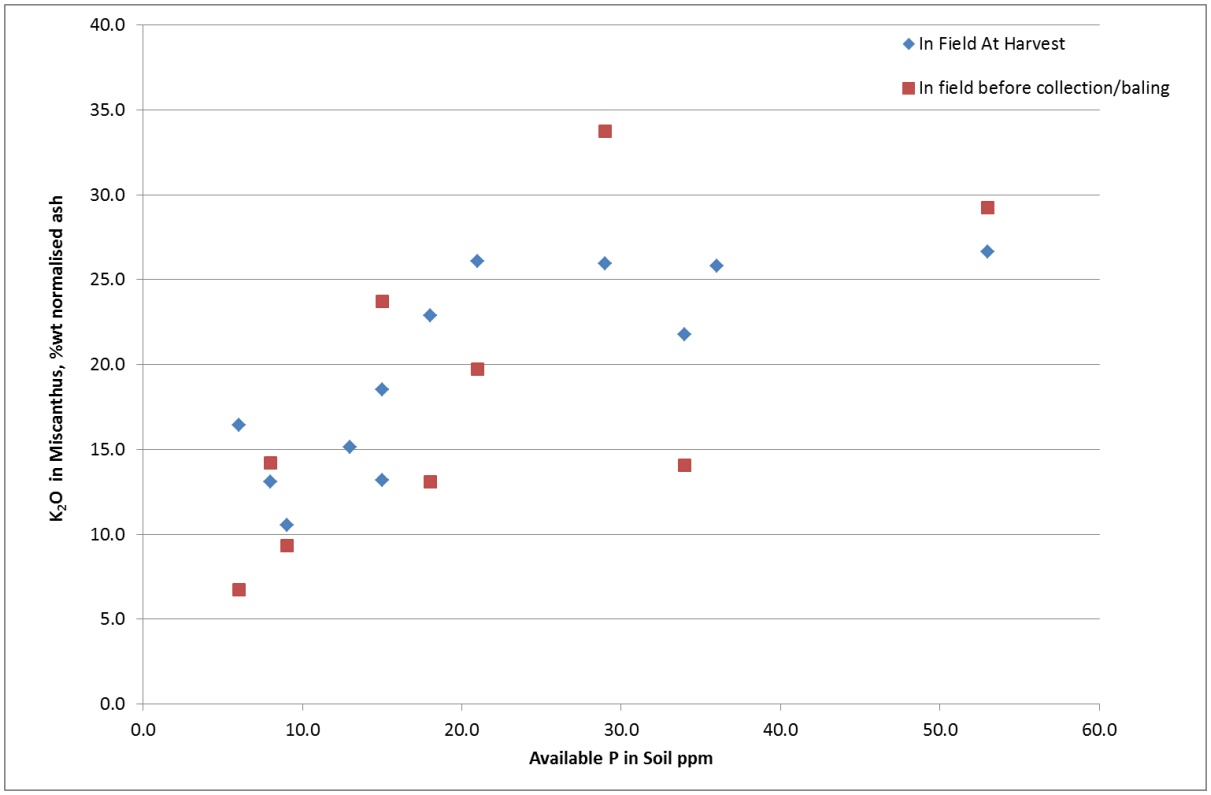
Determining the factors of greatest importance to feedstock characteristics can only be done in a qualitative way by review of the statistical analyses performed. For *Miscanthus*, the structured factors were climate zone, soil type and storage. The other statistical analyses to be considered are the correlations with soil characteristics and the correlations with site information (where these were possible).

Of the structured factors, climate zone significantly influenced the greatest number of measured feedstock characteristics followed by storage, with relatively few impacts from soil type. Storage decreased moisture content and consequentially increased net calorific value, but did not significantly affect any of the trace elements or macro-elements. Contrary to our expectation the measured soil type had only a limited impact.

As discussed in Section 2.6.3, the total variation explained by these structured factors was quantified using REML; the result of this (for all feedstocks) is presented in Appendix 9. This explained around 50 % of the total variation in moisture content and net calorific value.

The limited impact of soil type is consistent with the low number of significant correlations found between soil chemistry and feedstock characteristics (see Appendix 5) One of the strongest positive correlations (61% probability) identified was between soil phosphate levels and the oxide K_2O in the feedstock analysis (see Figure 5-9). Where the phosphate level is high within a soil, the level of K_2O can be seen to increase in the feedstock ash.

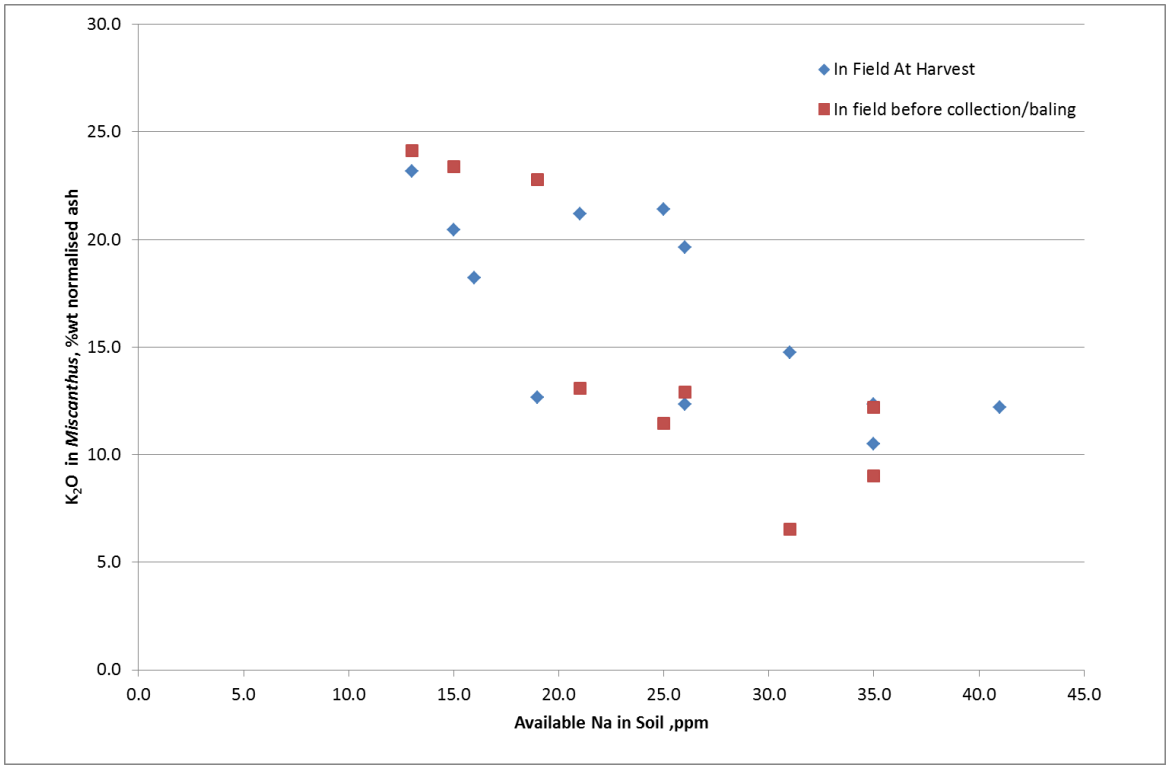
Figure 5-9: Correlation between K_2O concentration in *Miscanthus* ash and phosphorous in soil



The phosphate levels for the twelve *Miscanthus* individual field sites are very typical of average agricultural land type, with a typical range of 16-35 ppm of available phosphate; this is well within the average of UK soil concentrations. Levels of K_2O increased from 6.76 %wt to 33.74 %wt whilst soil phosphate levels increased from 6 ppm to 53 ppm.

Figure 5-10 shows where sodium levels of a soil increased, a reduction of K_2O could be seen in the feedstock, possibly because the *Miscanthus* was utilising the sodium in the soil in preference to available potassium.

Figure 5-10: Correlation between sodium in soil and K_2O concentration in *Miscanthus* ash



Sodium concentrations in the soils ranged from 13-43 ppm, while the K_2O levels in the *Miscanthus* ash varied between 6.54-24.12 %wt sodium concentrations in the soil are within UK agricultural land average levels.

Sodium level in the soils did not affect the Na_2O level in the feedstock ash, with the range of Na_2O remaining relatively consistent as the sodium level of soil increased.

Levels of K_2O in the ash were found to increase with increasing sand content in the soil and decrease as the silt percentage increased, as shown in Figure 5-11 and Figure 5-12.

There appeared to be no clear correlation between the percentage of clay in the soil and any of the macro elements or oxides found in the feedstock.

Other less marked correlations can be seen between the soil pH and the level of the ash oxide Mn_3O_4. As soil pH increases the level of Mn_3O_4 in the feedstock was seen to slightly reduce. Likewise, as levels of calcium in the soil increased there was a slight correlation showing a reduction in the ash oxide K_2O levels.

Planting year, which ranged from 2005 to 2011, affected only cadmium concentrations in the feedstock, as seen in Figure 5-8.

The various influences described above have been collated, focussed on the variables thought in the team's expert opinion to be important in a commercial operational context, and ranked in a qualitative way. Table 5-5 must be treated with caution but nevertheless indicates that feedstock characteristics are not affected in a consistent way by the site properties and crop management. The implications for growers are that the most important factor affecting moisture and NCV, i.e. storage, can be manipulated, while some of the chemical properties might be modified by the selection of fields within their land holding, or the age of the rhizome system. On the other hand most of the key macronutrients are primarily dependent on the climate zone. At first glance, the grower has minimal influence on the climate zone of their

land holding, however for an annual crop like *Miscanthus,* the observed impact of climate zone is likely to be due to the local weather via temperature, availability of water and radiation. It is possible that with a better understanding of these impacts, sections of the farm could be chosen that would optimise the feedstock properties, provided yield was not adversely affected. The implications for buyers are that consideration must be given to the feedstock characteristics of prime importance in a particular application.

Table 5-5: Factors influencing key feedstock characteristics of *Miscanthus* ranked in order of decreasing importance.

Variable	Rank 1	Rank 2	Rank 3
Moisture, %wt (ar)	Storage	Soil type	Climate zone
NCV kJ/kg (ar)	Storage	Soil type	Climate zone
Ash, %wt (d)	Climate zone	Storage	Soil type
$CaCO_3$, %wt (na)	Climate zone	Soil type	Storage
MgO, %wt (na)	Climate zone	Soil type	Storage
K, mg/kg (d)	Climate zone	Soil type	Storage
Si, mg/kg (d)	Climate zone	Soil type	Storage
Alkali Index	Climate zone	Soil type	Storage
MgO, %wt (na)	Soil type	Climate zone	Storage
Mg, mg/kg (d)	Soil type	Storage	Climate zone
P, mg/kg (d)	Soil type	Climate zone	Storage
Cd, mg/kg (d)	Planting year		
K_2O, %wt (na)	% silt in the soil	% sand in the soil	Available soil Na, Available soil P

Figure 5-11: Correlation between soil sand content and K_2O concentration in *Miscanthus* ash

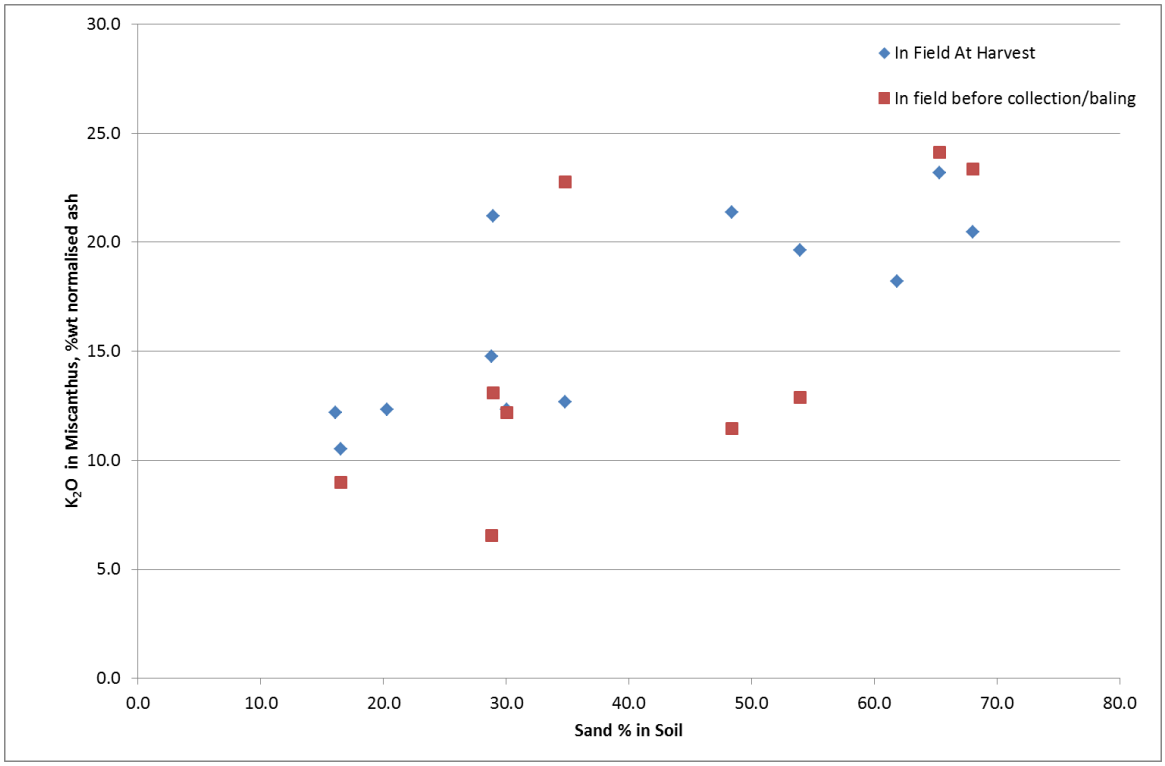
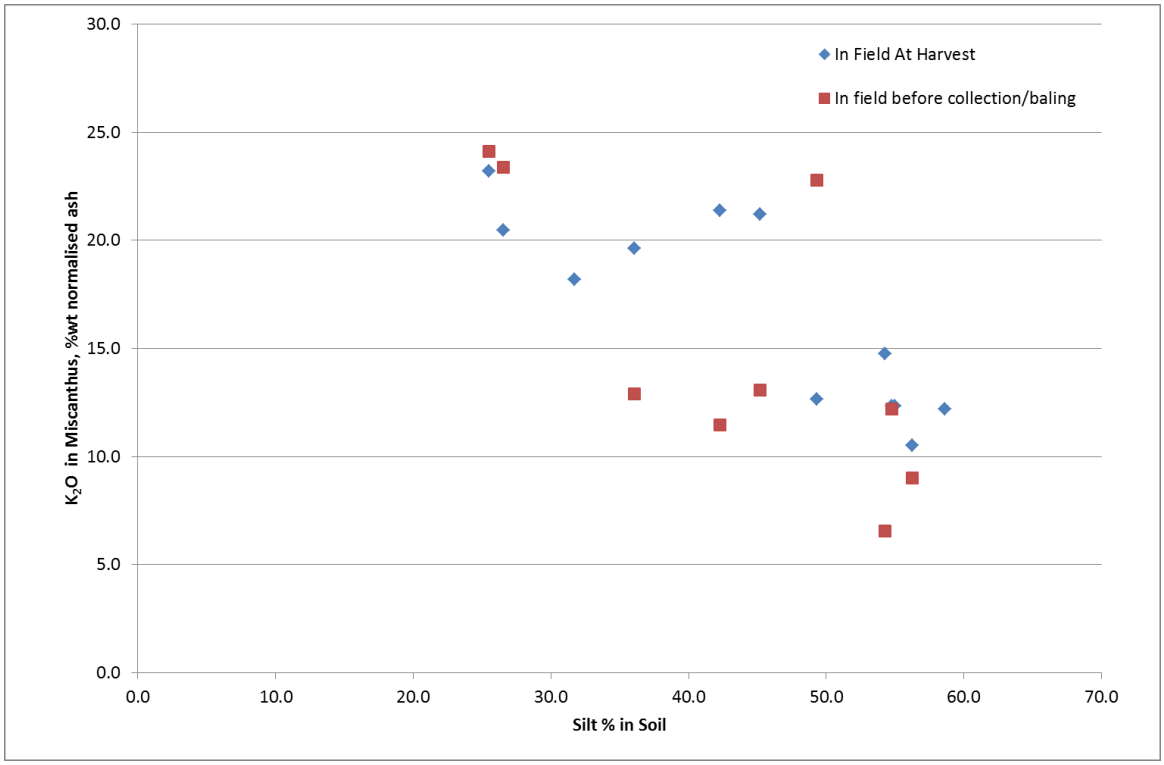


Figure 5-12: Correlation between soil silt content and K_2O concentration in *Miscanthus* ash



5.5 In-field variation

At each of the three in-field variation sites (numbered sites 082, 083 and 084 in D4 but referred to here as sites IFV1-3 respectively), 20 biomass samples were collected and analysed separately which allowed the variability within each field to be investigated. Site maps indicating the location of each sampling location within the field and the changes in elevation

(metres above sea level) as you travel from sample location 1→20 are given in Figure 5-13 to Figure 5-15. For these maps (and the equivalent maps in the willow in-field variation Section 6.5), each sampling location is marked by a yellow pin (which corresponds in number to the sample identifier in the D4 database). The profile map at the bottom of each map follows the route from location 1 to location 20. The mean value (excluding outliers) and the coefficient of variation for each of the sites are presented in Table 5-6. The final two columns in this table split the total variance within the 60 *Miscanthus* samples into the variance between the three sites and the variance with the 20 samples from each infield location. These columns have been shaded to indicate when over 66% of the variance was between the sites or within the sites.

By comparing the variance in feedstock characteristics, it is clear from Table 5-6 that for some feedstock characteristics (for example moisture and barium content), the variation between the sites was greater than that within the samples from the same field. For other characteristics (e.g. ash %) levels of variation between sites and within field were similar. Finally, for other characteristics (e.g. many trace elements), the variation within-field was much greater than that from one site to another. These patterns could be explained as follows:

- elements such as nitrogen and potassium, which are commonly added as fertilisers in a uniform rate across the field, are equally variable between and within fields reflecting the past pattern of fertiliser applications
- trace elements, which would not be added to fields, tend to be tightly bound to soil complexes so the patterns will tend to reflect the distribution of both the source of the trace elements and soil complexes that bind them with the result that the trace elements are highly variable within a field yet there is limited variability from one field to another
- elements such as calcium, magnesium and phosphorus are more abundant than the trace elements and would not normally be added as fertilisers yet unlike the trace elements they are moderately mobile, consequently each field is relatively uniform but the general level of these elements is determined by the parent material which will vary at a landscape scale. Over time the overall pattern is one of greater variation between than within sites.

Examples of the most interesting observations for the in-field variation are illustrated below. Moisture levels in the *Miscanthus* were highly site specific, as illustrated in Figure 5-16, but the values were within the range seen across all the twelve different sites that were sampled for *Miscanthus* in Study 1 (“other sites” category). Further graphs for the in-field feedstock parameters are available in Appendix 8.

Figure 5-13: Site map for *Miscanthus* IFV1 (site 082)

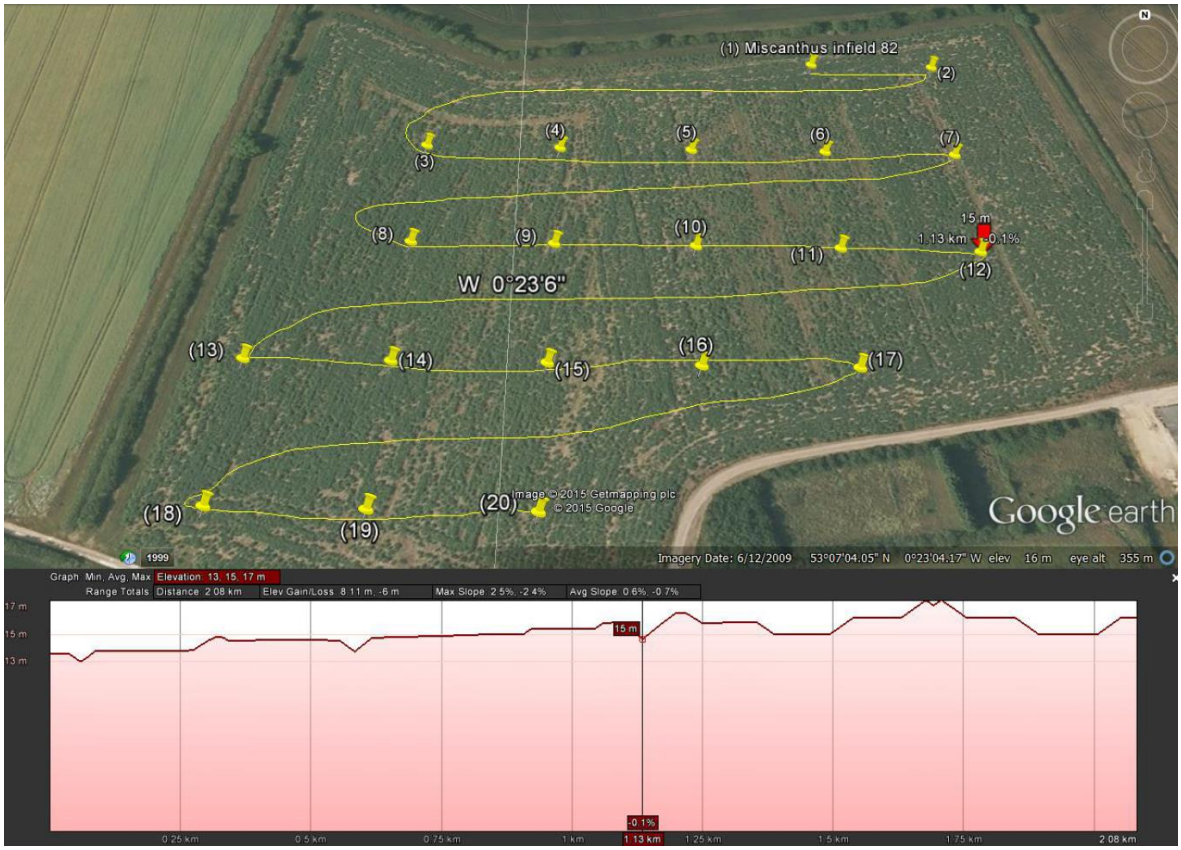


Figure 5-14: Site map for *Miscanthus* IFV2 (site 083)

Figure 5-15: Site map of *Miscanthus* IFV3 (Site 084)

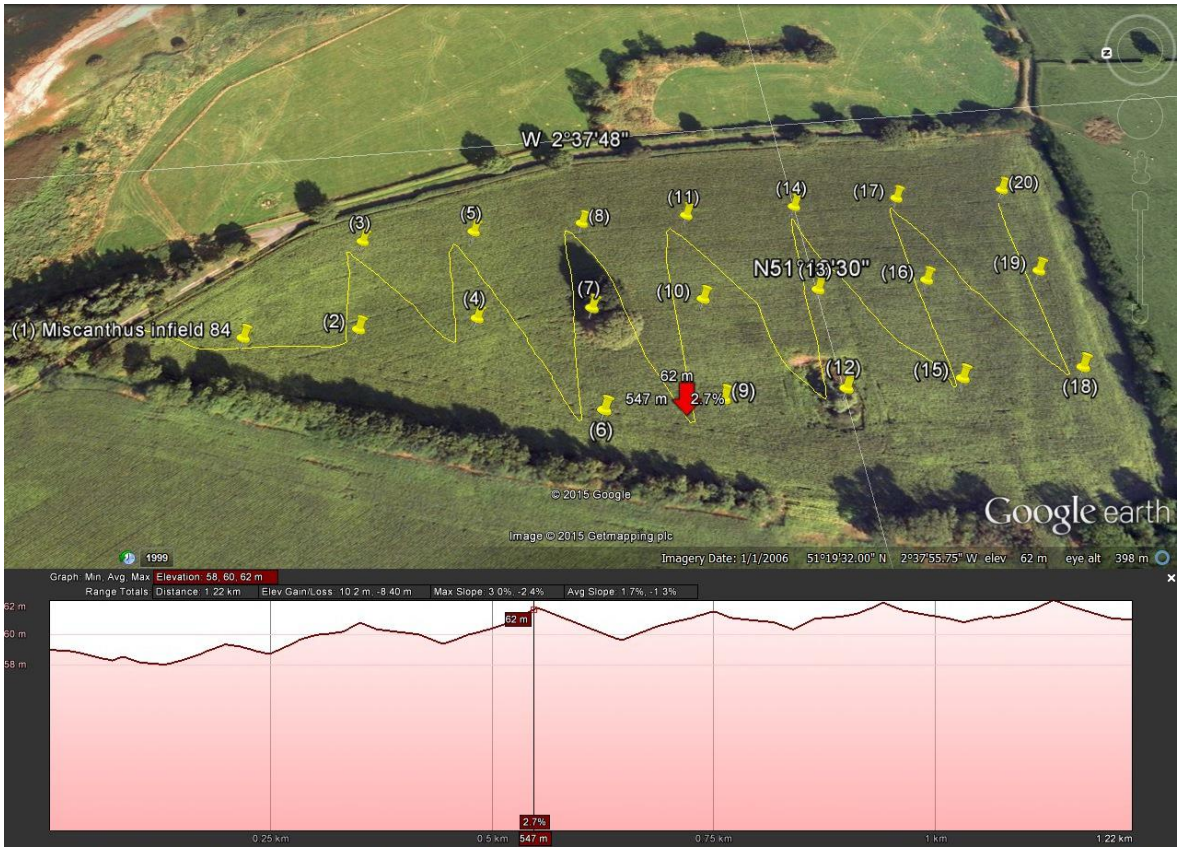


Table 5-6: Mean values and variance for the *Miscanthus* in-field variation

	IFV 1 (site 082)		IFV 2 (site 083)		IFV 3 (site 084)			
Variable	Mean	Coefficient of Variance %	Mean	Coefficient of Variance %	Mean	Coefficient of Variance %	Variance between sites relative to total variance (%)	Variance within sites relative to total variance (%)
Moisture (ar)	38.3	7.73	13.8	16.46	20.7	8.78	92.16	7.84
Net calorific value (ar)	10125	6.09	14829	6.92	13757	2.82	91.98	8.02
Ash content (d)	2.4	14.43	2.3	10.79	2.0	6.73	38.17	61.83
Volatile matter (DAF)	82.0	1.24	82.4	0.85	83.6	1.29	42.23	57.77
Gross calorific value (DAF)	19669	0.49	19578	0.46	19675	0.56	20.13	79.87
Carbon (DAF)	50.14	0.24	49.32	0.63	49.29	0.93	68.24	31.76
Hydrogen (DAF)	6.06	0.7	6.07	1.26	6.10	0.81	9.12	90.88
Nitrogen (DAF)	0.53	11.45	0.36	13.03	0.39	18.4	64.63	35.37
Sulphur (DAF)							10.53	89.47
Chlorine (DAF)	0.20	14.39	0.15	18.57	0.11	30.81	73.57	26.43
Barium (d)	2.76	21.07	6.93	13.49	20.57	14.8	96.14	3.86
Chromium (d)	0.50	224.08	0.13	14	0.13	23.78	5.57	94.43
Cobalt (d)	0.15	70.53	0.12	8.51	0.10	6.65	10.28	89.72
Copper (d)	3.04	126.91	2.09	8.38	1.62	23.47	5.1	94.9
Molybdenum (d)	0.21	80.16	0.29	25.77	0.11	7.64	43.51	56.49
Nickel (d)	0.13	14.3	0.12	8.7	0.10	7.16	0.65	99.35
Vanadium (d)	0.19	96.13	0.12	8.61	0.10	6.83	13.27	86.73
Zinc (d)	8.02	23.32	23.36	14.08	24.78	19.35	87.69	12.31
Antimony (d)							5.8	94.2
Arsenic (d)							1.5	98.5
Mercury (d)							0	100
Bromine (d)							74.85	25.15
Cadmium (d)	0.02	106.62	0.09	39.1	0.3	47.28	74.81	25.19
Lead (d)	1.28	216.73	0.64	314.47	0.95	242.58	0	100
Al_2O_3 (na)	0.24	47.9	0.19	15.38	0.12	22.41	38.38	61.62

	IFV 1 (site 082)		IFV 2 (site 083)		IFV 3 (site 084)			
Variable	Mean	Coefficient of Variance %	Mean	Coefficient of Variance %	Mean	Coefficient of Variance %	Variance between sites relative to total variance (%)	Variance within sites relative to total variance (%)
BaO (na)	0.06	88.54	0.04	15.42	0.12	21.88	60.05	39.95
$CaCO_3$ (na)	22.29	11.31	11.28	12.32	11.63	21.74	88.84	11.16
Fe_2O_3 (na)	1.86	371.25	0.15	11.48	0.11	34.6	1.24	98.76
K_2O (na)	24.2	10.81	25.11	12.63	19.5	24.64	38.67	61.33
MgO (na)	3.7	12.54	3.87	11.84	3.53	18.6	4.68	95.32
Mn_3O_4 (na)	0.15	31.23	0.29	30.29	0.97	35.09	81.89	18
Na_2O (na)	0.54	15.69	0.62	10.17	0.62	21.74	13	87
P_2O_5 (na)	7.2	21.39	7.26	15.27	3.25	29.31	77.61	22.39
SiO_2 (na)	39.68	11.26	51.16	8.3	60.12	9.91	80.89	19.11
TiO_2 (na)	0.08	53.71	0.04	125.33	0.03	120.57	22.63	77.37
Aluminium (d)							44.91	55.09
Calcium (d)							86.76	13.24
Iron (d)							1.02	98.98
Potassium (d)							44.89	55.11
Magnesium (d)							25.05	74.95
Manganese (d)							82.26	17.74
Sodium (d)							3.29	96.71
Phosphorous (d)							76.02	23.98
Silicon (d)							42.4	57.6
Titanium (d)							29.63	70.37
Alkali index							44.94	55.06

Pink shaded cells indicate where over 66% of the total variance was either between sites or within sites

IFV sites 1 and 3 were sampled almost one month earlier than IFV site 2, indicating that the average moisture content reduced from early March (IFV1) to late March (IFV3) (Figure 5-16). The lowest recorded moisture sample was almost one month later in April (IFV2). This trend is also apparent for the nitrogen levels within the collected samples, as shown in Figure 5-17.

Figure 5-16: Results from the moisture analysis of *Miscanthus* for in-field variation sites of Study 2 (study 1 values also provided for comparison)

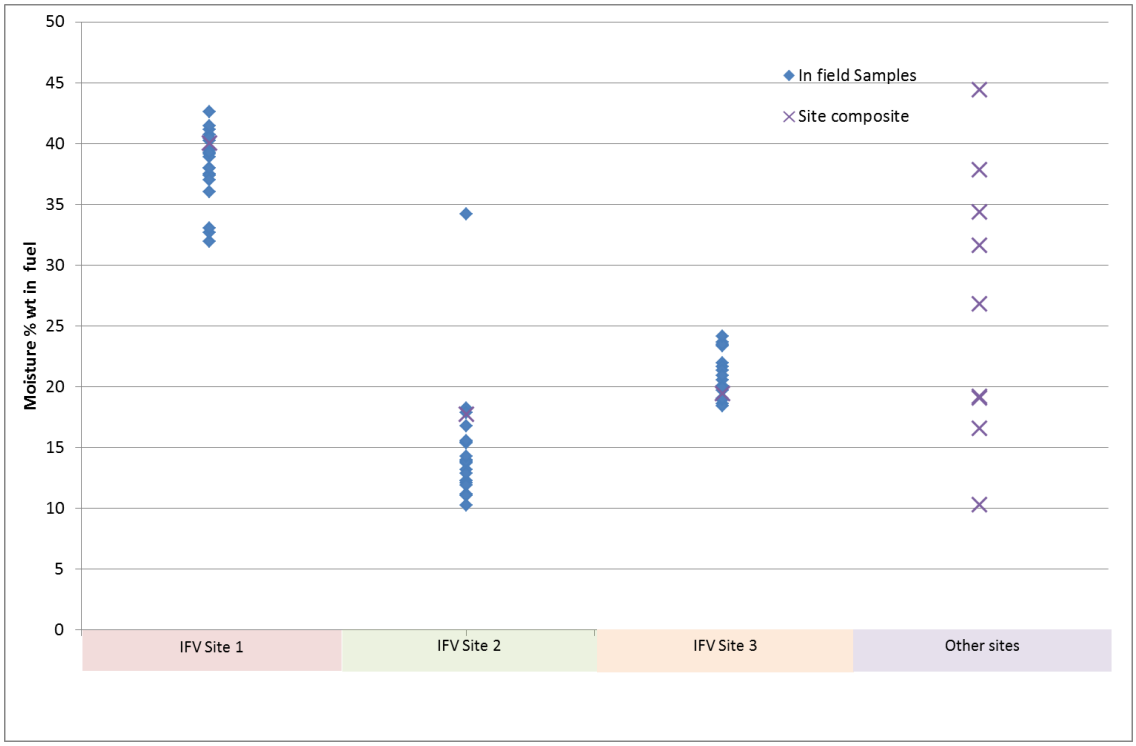
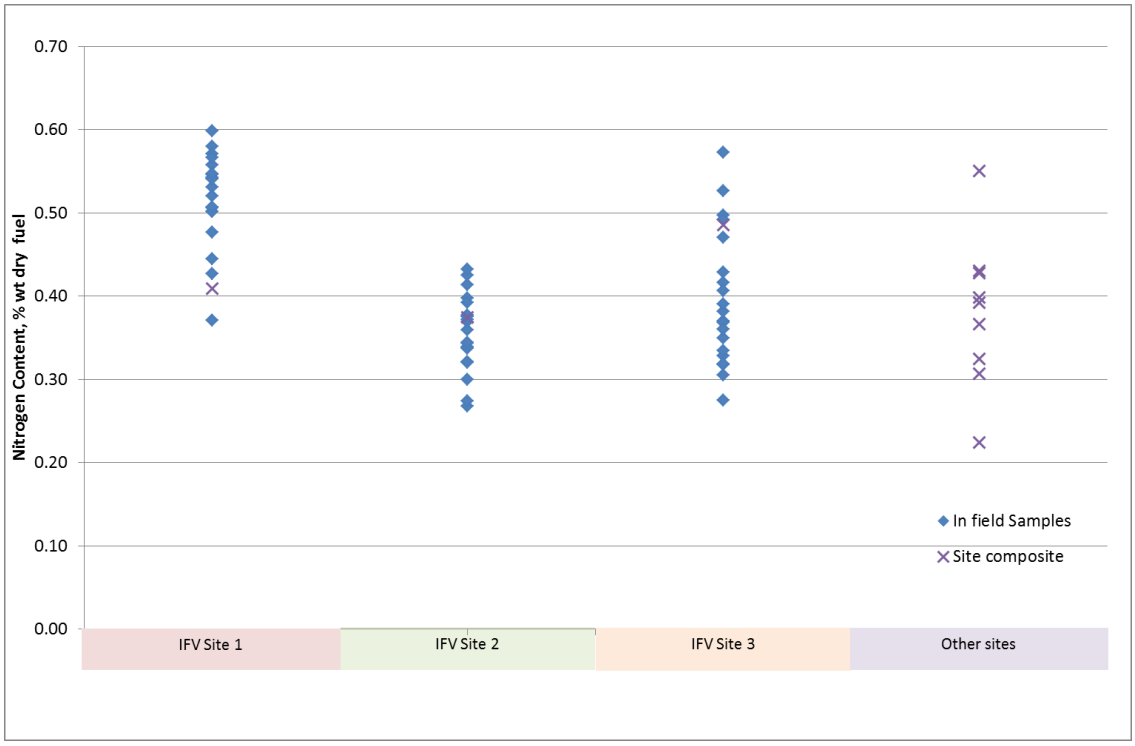
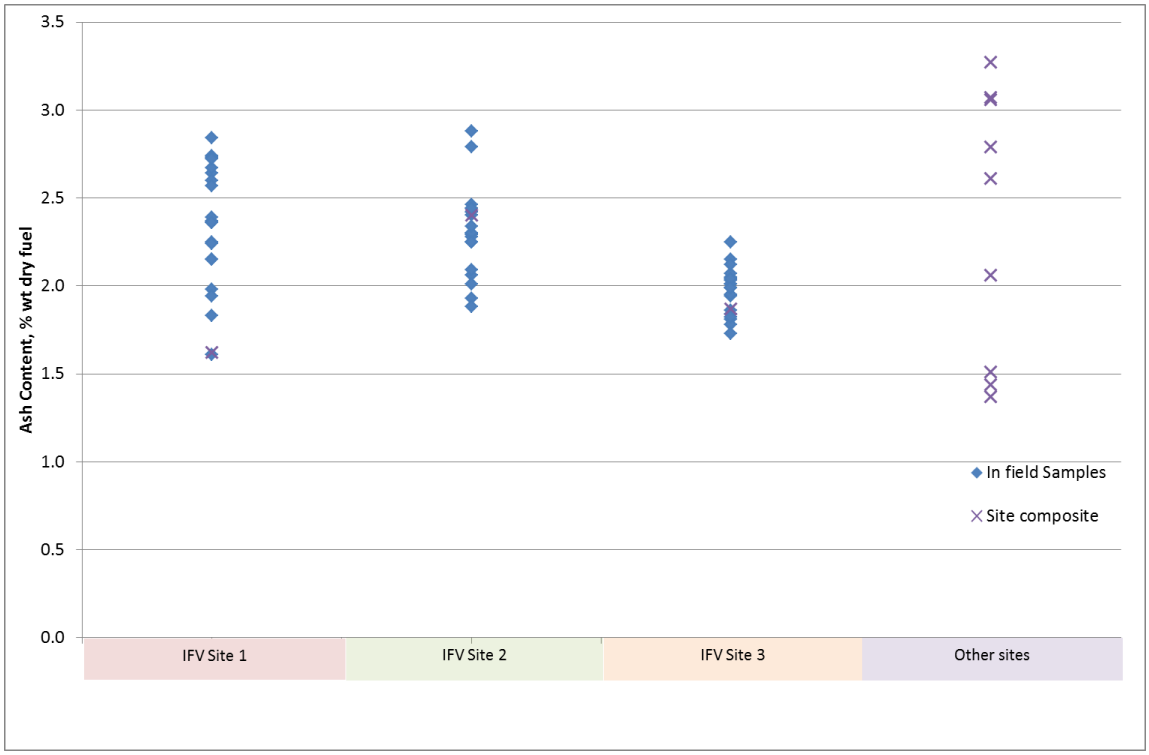


Figure 5-17: Results from the nitrogen analysis of *Miscanthus* for in-field variation sites (study 1 values also provided for comparison)



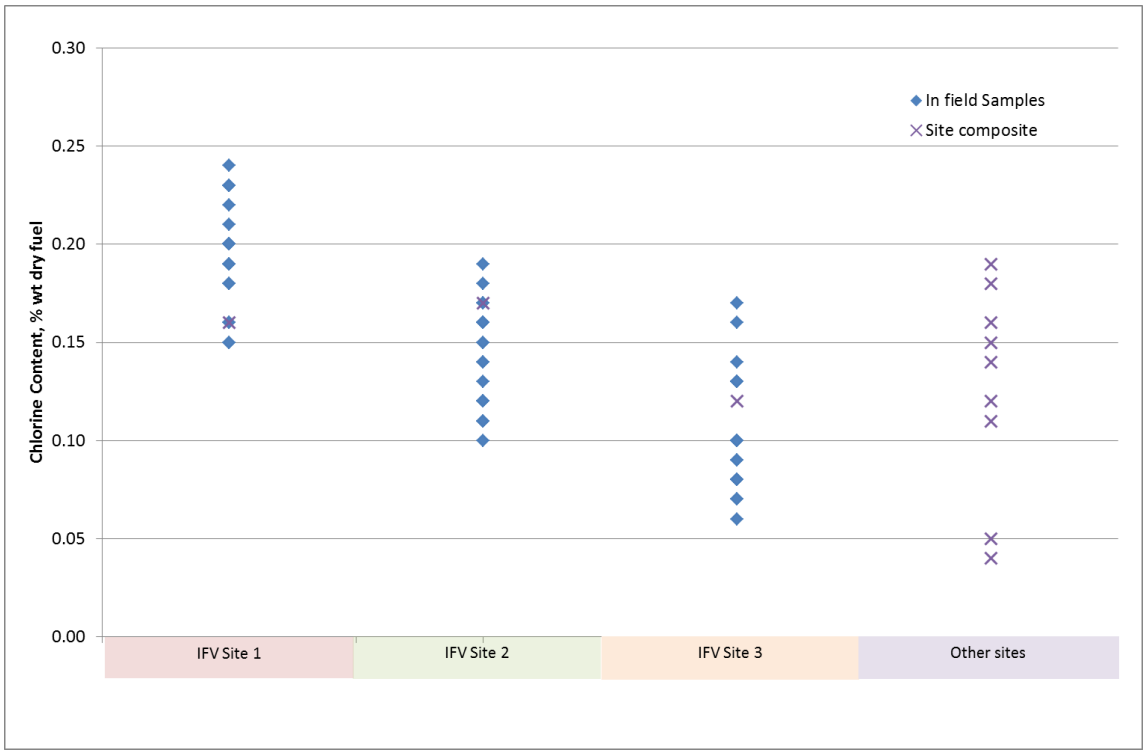
Ash content was more consistent across all sites; see Figure 5-18, although the data from Site 3 was notably more clustered than from the others.

Figure 5-18: Results from the ash analysis of *Miscanthus* for in-field variation sites (study 1 values also provided for comparison)



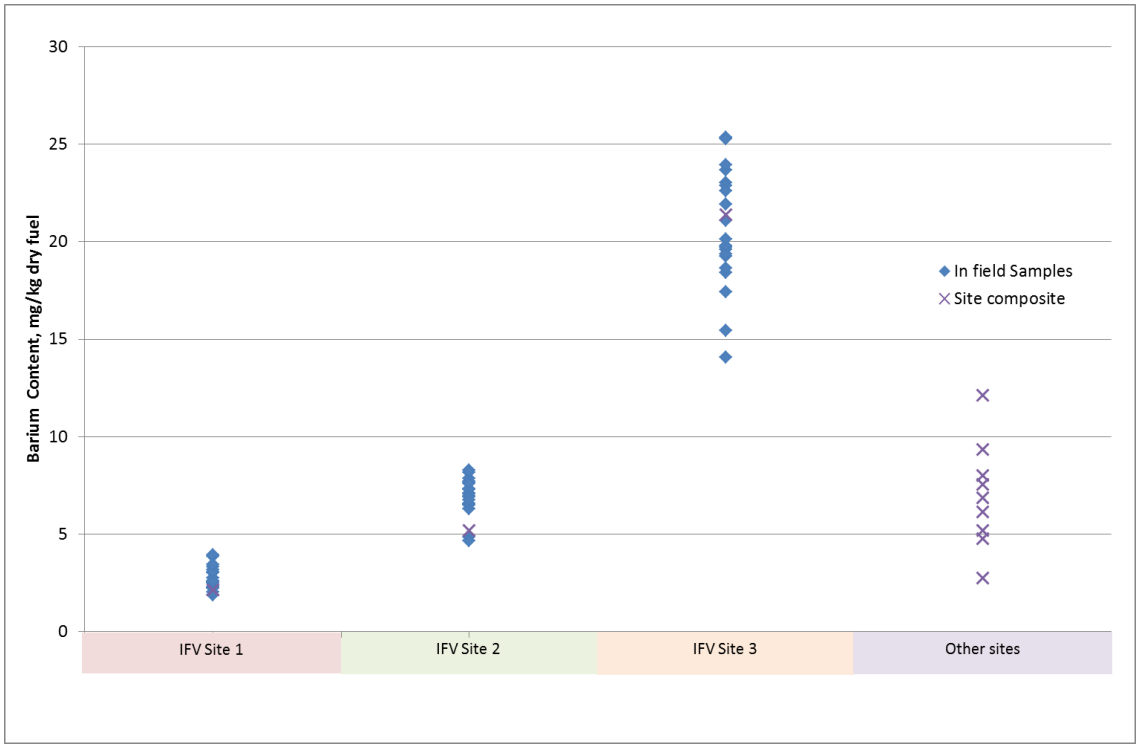
The behaviour of chlorine was of significant interest and Figure 5-19 illustrates the variation between and within sites.

Figure 5-19: Results from the chlorine analysis of *Miscanthus* for in-field variation sites (study 1 values also provided for comparison)



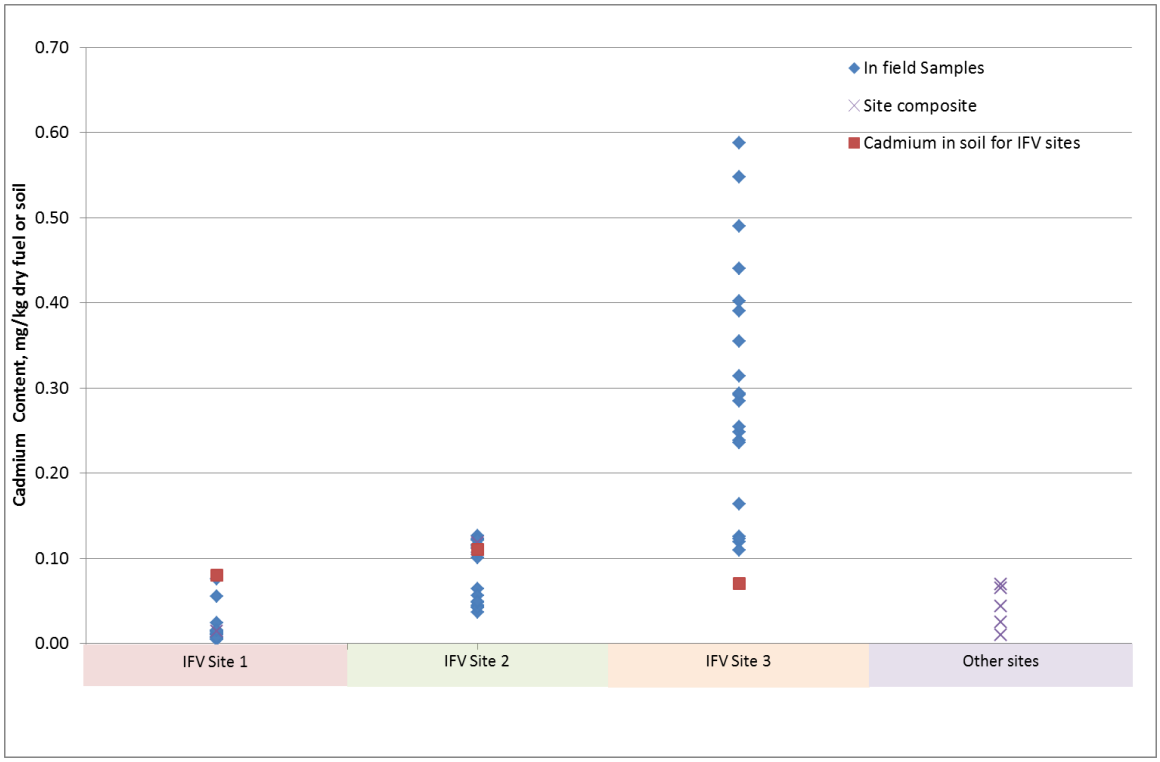
Of the trace element species, barium has the most striking variation between sites as illustrated in Figure 5-20, with samples from site 3 containing much higher and more variable concentrations than the other sites. Unfortunately, the soil samples were not analysed for barium, making it impossible to explain the cause of this observation.

Figure 5-20: Results from the barium analysis of *Miscanthus* for in-field variation sites (study 1 values also provided for comparison)



Cadmium showed a broadly similar pattern to barium, i.e. it was significantly higher in IFV 3 as shown in Figure 5-21; cadmium was also determined in the soils, but IFV 3 soil did not contain the highest levels of cadmium. Other characteristics showing a notable variation between sites included bromine, molybdenum, zinc, calcium, manganese and phosphorous (as shown in Appendix 8).

Figure 5-21: Results from the cadmium analysis of *Miscanthus* and soil for in-field variation sites

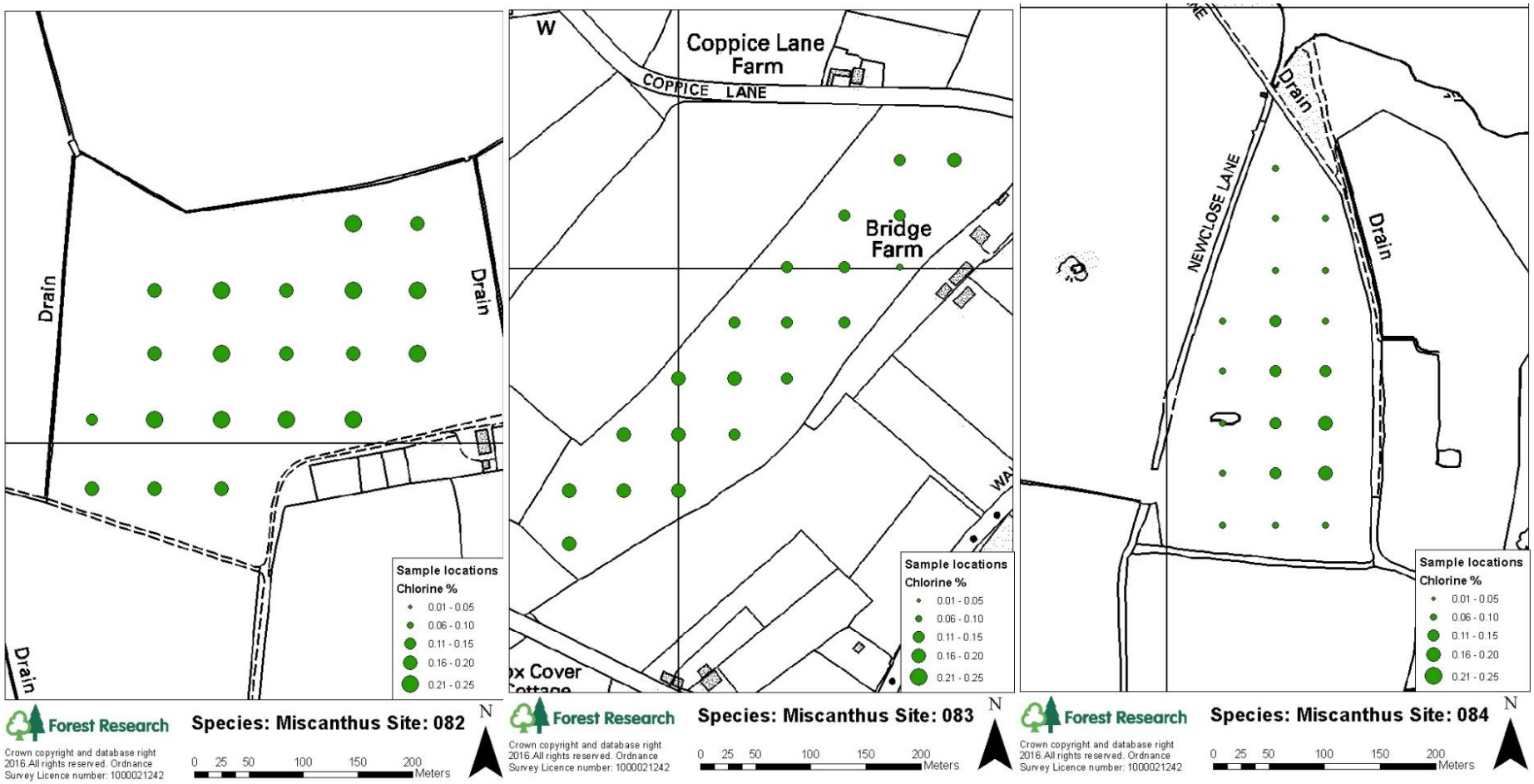


In order to visualise the variability of characteristics within each field, the results of the feedstock analysis and certain site provenance data collected for individual sampling points have been overlaid onto site plots, with the size of individual points indicating the magnitude of the parameter at that point. Example plots are shown for lead and chlorine in Figure 5-22; these show examples where the majority of the variability was within individual sites or between the three sites respectively (as indicated by Table 5-6). Further examples of these plots, including provenance data such as soil and air temperature at the time of sample collection, are provided in Appendix 4.

Figure 5-22: Concentrations of (a) lead and (b) chlorine in *Miscanthus* samples taken at different in-field sites (Site 082 = IFV1, Site 083 = IFV2, Site 084 = IFV3)

a)

b)


Drain
Drain
Drain
Sample locations
Chlorine %
0.01 - 0.05
0.06 - 0.10
0.11 - 0.15
0.16 - 0.20
0.21 - 0.25
Forest Research
Species: Miscanthus Site: 082
Crown copyright and database right 2016.All rights reserved. Ordnance Survey Licence number: 1000021242
0 25 50 100 150 200 Meters
N
W
Coppice Lane Farm
COPPICE LANE
Bridge Farm
Sample locations
Chlorine %
0.01 - 0.05
0.06 - 0.10
0.11 - 0.15
0.16 - 0.20
0.21 - 0.25
Forest Research
Species: Miscanthus Site: 083
Crown copyright and database right 2016.All rights reserved. Ordnance Survey Licence number: 1000021242
0 25 50 100 150 200 Meters
N
NEWCLOSE LANE
Drain
Drain
Sample locations
Chlorine %
0.01 - 0.05
0.06 - 0.10
0.11 - 0.15
0.16 - 0.20
0.21 - 0.25
Forest Research
Species: Miscanthus Site: 084
Crown copyright and database right 2016.All rights reserved. Ordnance Survey Licence number: 1000021242
0 25 50 100 150 200 Meters
N

5.6 Conclusion and hypothesis

Relevant hypotheses:

- The feedstocks examined range from *Miscanthus*, through woody deciduous plants grown for only a few years and regenerated by coppicing, to small deciduous and evergreen trees; therefore we hypothesise that the feedstocks will differ in their fuel properties and/or composition. This was discussed in Section 4.2.
- Feedstock properties will differ depending on the climate the crop is exposed to. Some feedstock properties differed with climate zone. The data available suggest that moving from warm/moist to a warm/dry climate was associated with a slight increase in ash content with consequent increases in two of the major species associated with ash: potassium and silicon. The concentrations of the oxides $CaCO_3$ and MgO in the ash itself are slightly reduced.
- Feedstock properties will differ depending on the soil composition and characteristics of the site. A small number of feedstock properties differed with soil type. A reduction in magnesium (both expressed as the element and as the oxide in ash) and iron oxide in ash, and an increase in phosphorous were also observed on moving from a light to medium soil type; this could partly be expected as medium soils are typically expected to contain more phosphate.
- Feedstock properties will differ with storage. There was a strong effect of storage, decreasing moisture content and increasing net calorific value
- Within a given field, feedstock properties will be relatively uniform There is no simple conclusion regarding the variation within fields compared to the variation between fields. For some feedstock characteristics (for example moisture and barium), the variation between the sites was greater than that within the samples from the same field. For others, (e.g. many trace elements), the variation within-field was much greater than that between different sites.

Although heavier soils should easily support the growing of a *Miscanthus* crop, as establishment on this soil type is difficult, commercial planting companies have tended to avoid heavy soil types in more recent years, and this is why no *Miscanthus* samples were able to be taken from heavy soils for this project.

Although there is a general expectation that soil properties will influence crop characteristics, this was not borne out by our findings. Within the range of light and medium soil sampled, soil type had only a limited effect on feedstock characteristics. Moreover, feedstock characteristics and actual soil analysis data proved largely to be unconnected, although sand /silt as well as sodium and phosphorous in soils were shown to be correlated with K_2O in the feedstock. The relative lack of correlations between macroelements in soils and feedstocks outcome does tend to oppose other research, (Shield *et al*., 2014) which shown impacts of soil and fertiliser application values impacting on feedstock characteristics.

The usual *Miscanthus* harvest timing in the UK is March to April, but can be as early as February with some very dry sites, or where early senescence has occurred. There is some indication from Study 2 that samples from the earlier harvests had higher moisture content. The most important experimental factor was the impact of storage on moisture content and consequentially NCV. The average moisture content dropped from >25% to 15% by performing good harvest management practices, of cutting and then waiting for several weeks

before baling the cut product. It is interesting to see in Figure 5-4 that the range in moisture content also decreased with storage, indicating that the feedstock was becoming more consistent. Possible benefits of storage can also be seen in the levels of chlorine, which were seen to marginally reduce between harvesting time and collection/baling time (Figure 5-7). Taken together, these findings emphasise that after-care storage and good harvest management are essential in achieving and maintaining the best quality product.

The data available suggest that moving from warm/moist to a warm/dry climate was associated with a slight increase in ash content with consequent increases in two of the major species associated with ash: potassium and silicon. The concentrations of the oxides $CaCO_3$ and MgO in the ash itself are slightly reduced. A reduction in magnesium (both expressed as the element and as the oxide in ash) and iron oxide in ash, and an increase in phosphorous was also observed on moving from a light to medium soil type; this could partly be expected as medium soils are typically expected to contain more phosphate.

Miscanthus has commonly been used and investigated (as has willow SRC) for use as a land remediation plant because the plants are highly efficient at removing elements (in particular heavy metals) from contaminated soils (Nsanganwimana *et al*., 2014). Little, if any, evidence was seen for correlations between heavy metal content of soils and *Miscanthus*, but it should be noted that none of the sites samples as part of this project would be viewed as ‘contaminated’.

6 Willow SRC

6.1 Introduction

Willow has been cultivated for many decades in the UK for bio-energy. The UK has in excess of 300 different willow strains, with around 10% of these being suitable for use as high yielding dedicated bioenergy crop varieties (Karp *et al.*, 2011). Typically the plants are established at high density (10,000-25,000/ha) for bioenergy production, and are planted as rods, which are usually 40 cm long. After one growing season, each plant is typically cut back (variety-specific management) to help promote the production of multiple stems (and to enable good weed control). Stems are harvested for energy use usually after three more growing seasons, with two - to four-year intervals more commonly being used with newer varieties, giving rise to the general description of 'short rotation coppice'. Typical UK yields are 8 ODT/ha/yr for traditional varieties with newer varieties reportedly able to achieve 12-15 ODT/ha/yr. Current breeding programmes are aiming to produce varieties achieving 18 ODT/ha/yr by 2020 (Macalpine *et al.*, 2014).

The genetic make-up of planting stock has received considerable attention since the 1980s, the aim being to produce crosses that combine good growth rates and suitable stem form with resistance to pests and diseases. Since pest and disease resistance of a given variety can breakdown, commercial growers usually plant a mix of varieties within a commercial planting; this doesn't stop the disease or pest from damaging the crop, but does help to reduce the potential impact of an infection should one occur. Willow breeding programmes are making improvements to the main breeding stock on a continual basis, making new varieties commercially available.

Plantations typically last 5-6 rotational cycles (20-24 years), before all roots/stumps become exhausted or the stem/growth produced is not sufficient for an economically viable enterprise; at this point in time the crop must be removed (roots as well) and replanted. The total plantation length can be shorter or longer depending on the typical harvest interval used, and the general plantation management applied. If plants suffer from disease or pest attacks on a regular basis then the total plantation lifecycle is likely to be adversely affected. Likewise if weed control in early years of establishment and following each harvest is not managed effectively this can cause stump/root losses due to competition by weeds.

Willow in general terms is suited to moderately high soil moisture availability and warm climates though it can be grown on a range of soil types and cooler climates.

The variability of willow SRC was investigated in three different site-related studies. In a similar experimental matrix to that adopted for *Miscanthus*, the first study related to taking samples across different sites, whilst the second study focussed on assessing the variability within three particular sites which was similar to the *Miscanthus* in-field study. The final study on willow SRC involved sampling the leaves only. The results from all these studies are considered in this section (see Figure 6-1 for the geographical location of the relevant sites).

Study 1 investigated the effect of the climate zone (warm/moist, warm/dry), actual soil type (light, medium) and storage on feedstock quality. There were two sampling exercises on the same material to investigate the effect of storage. The first samples were collected just as the coppice was being harvested and the second after the willow chips created at harvesting had been stored in heaps for one month.

One representative sample was analysed from each site location at each sampling time. For the fresh samples, one site sample was formed as a composite of subsamples taken from at least 10 locations within the site, before being bulked, thoroughly mixed, and sampled for analysis.

Because of the sampling design, this study also allowed the interactions between these factors to be investigated, for example the response to storage could be different in warm/moist climate zones compared to warm/dry climate zones.

To investigate the importance of these factors in a robust statistical way, the original design intended that there were three sites in each combination of climate zone, soil type and storage time. For reasons described in Section 2.4, a full set of sites could not be identified – in fact six sites rather than the intended twelve were located and unfortunately these gave poor representation of warm/moist site locations (see Table 6-1).

Table 6-1: Number of willow SRC sites sampled in each combination of storage, soil type and climate zone.

		Soil Type	
Storage	Climate Zone	Light	Medium
In field at harvest	Warm/dry	3	2
	Warm/moist	0	1
After 1 month's storage	Warm/dry	3	1*
	Warm/moist	0	0*

*Two of the sites were unavailable for sampling after storage

The sampling design used in Study 1 allowed the interactions between these factors to be investigated, for example the response to storage could be different in light compared to medium soils. Results from this structured analysis are presented in Section 6.2.

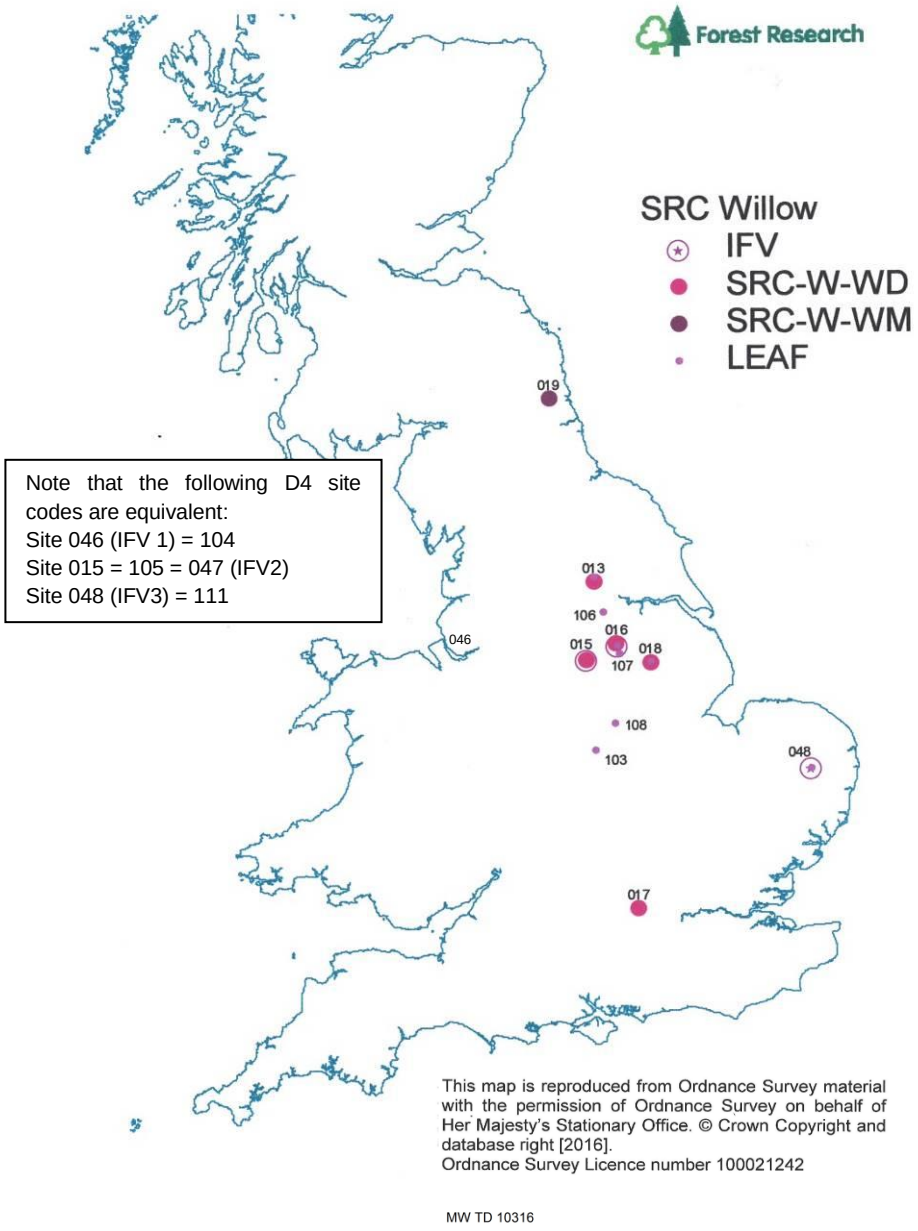
Further information on many aspects of each site was collected for the purpose of understanding reasons for any observed differences in the feedstock characteristics. The provenance information included management factors as discussed in Section 3.2

Study 2 investigated the variation within sites, also referred to as 'in-field variation'. At each of three in-field variation sites, 20 biomass samples were collected and analysed separately which allowed the variation in feedstock characteristics within each field to be investigated. These data were also compared to the variability between different sites. The results are presented in Section 6.5.

In most commercial operations, willow SRC is harvested in winter after the leaves have fallen and before growth begins again in the spring. In recognition of the fact that some of the harvested plants might retain some leaves, willow leaves were sampled from three different sites for characterisation (Study 3).

Figure 6-1 shows the geographical location of the willow SRC sites sampled in Study 1, 2, and 3.

Figure 6-1: Location of willow SRC sampling sites (WD = warm/dry climate, WM = warm/moist climate, IFV = in-field variation sampling). Location numbers reference site codes used in D4.



6.2 Results of structured analysis on feedstock characteristics

For willow, the impact of climate zone could not be assessed as there were insufficient samples from warm/moist sites; therefore only soil type and storage were assessed. Table 6-2 provides an overview of the impact of these two experimental factors and their interaction. As discussed in Section 5.2, in Table 6-2, the closer the value is to zero, then the greater the influence of the structured factor on the parameter in question.

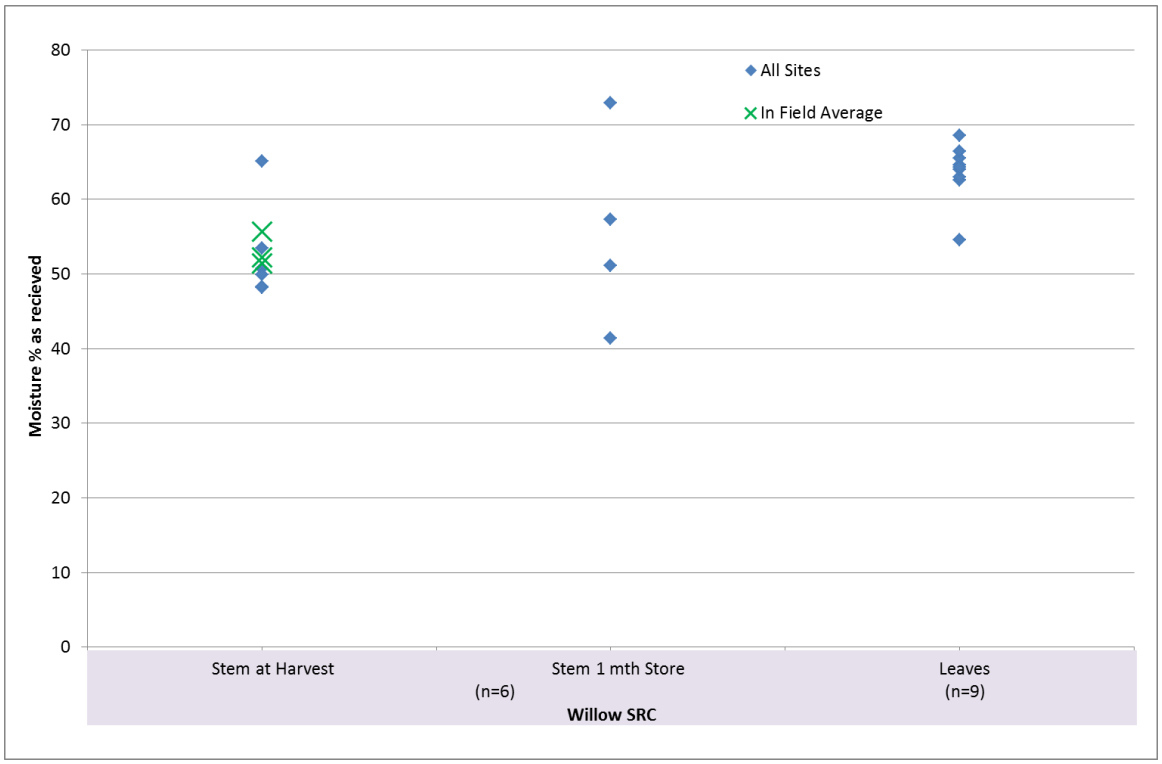
Table 6-2: Structured analysis for Willow SRC

Variable (basis†)	SOIL TYPE	STORE	SOIL TYPE & STORE
Moisture (ar)	0.192	0.353	0.087
Net calorific value (ar)	0.161	0.321	0.093
Ash content (d)	0.970	0.881	0.481
Volatile matter (DAF)	0.858	0.435	0.567
Gross calorific value (DAF)	0.891	0.900	0.111
Carbon (DAF)	0.943	0.003	0.000
Hydrogen (DAF)	0.907	0.384	0.000
Nitrogen (DAF)	0.537	0.981	0.366
Sulphur (DAF)	0.006	0.034	0.000
Chlorine (DAF)	0.884	0.186	0.789
Barium (d)	0.973	0.271	0.544
Chromium (d)	0.324	0.000	0.000
Cobalt (d)	0.272	0.042	0.000
Copper (d)	0.378	0.001	0.000
Molybdenum (d)	0.996	0.000	0.035
Nickel (d)	0.693	0.097	0.924
Vanadium (d)	0.543	0.062	0.758
Zinc (d)	0.549	0.000	0.004
Cadmium (d)	0.354	0.569	0.273
Lead (d)	0.853	0.248	0.375
Al_2O_3 (na)	0.098	0.115	0.775
BaO (na)	0.898	0.431	0.460
$CaCO_3$ (na)	0.627	0.559	0.621
Fe_2O_3 (na)	0.467	0.015	0.025
K_2O (na)	0.286	0.625	0.681
MgO (na)	0.400	0.327	0.809
Mn_3O_4 (na)	0.877	0.126	0.495
Na_2O (na)	0.305	0.848	0.935
P_2O_5 (na)	0.126	0.065	0.906
SiO_2 (na)	0.849	0.138	0.859
TiO_2 (na)	0.254	0.910	0.688
Aluminium (d)	0.154	0.026	0.160
Calcium (d)	0.740	0.465	0.188
Iron (d)	0.410	0.000	0.000
Potassium (d)	0.733	0.918	0.151
Magnesium (d)	0.635	0.734	0.128
Manganese (d)	0.789	0.199	0.184
Sodium (d)	0.358	0.476	0.059
Phosphorous (d)	0.625	0.591	0.263
Silicon (d)	0.717	0.101	0.397
Titanium (d)	0.112	0.527	0.879
Alkali index	0.748	0.918	0.160

* analysis not undertaken on antimony, arsenic, mercury or bromine
†basis of analysis; ar = as received fuel, d = dry fuel, DAF = dry, ash-free fuel, na= normalised ash. Dark blue cells indicate $p<0.001$; light blue cells $0.001<p<0.05$

The statistical analysis for willow highlighted just one impact from soil type and a large number of impacts due to storage. The majority of those characteristics impacted by storage were also affected by the combination of soil type and storage. It is interesting to note that compared to other feedstocks, one month's storage (as chipped material in uncovered heaps outside) had no impact whatsoever on moisture content of the willow, as illustrated in Figure 6-2, note these storage times are shorter than for the other woody biomass and normally a minimum of three months storage would be required to see a significant reduction.

Figure 6-2: Results from the moisture analysis of willow SRC



On closer inspection of the willow SRC data, it is apparent that of all of the impacts highlighted by the statistics, few, if any, are worthy of further discussion, even though many were identified as strongly significant (see Table 6-3). In certain cases the results were at the limit of detection or the difference was within analytical repeatability, but for the majority (mainly trace elements) the differences are judged to be operationally insignificant. The very small size of the willow dataset should also be noted. There were a total of just 10 willow samples across all conditions - meaning that certain combinations of climate zone and soil type are represented by a single sample.

Table 6-3: Mean values and assessment of relevance for main effects and interactions for parameters identified as significant in structured analysis of willow SRC

One factor analysis			
Variable	STORAGE		Assessment
	Fresh	Stored	
Number of analyses	6	4	
Al, mg/kg (d)	63.2	104.7	Unlikely to have operational impact

Two factor analysis				
Variable	Soil Type / Storage	Light	Medium	Assessment
Default Number of analyses	Fresh	3	3	
	Stored	3	1	
Carbon, %wt (DAF)	Fresh	50.98	49.98	Unlikely to have operational impact
	Stored	49.51	52.46	
Hydrogen, %wt (DAF)	Fresh	6.16	6.21	Exclude – within repeatability of analysis
	Stored	6.22	6.03	
Sulphur, %wt (DAF)	Fresh	0.01	0.01	Exclude – at or below limit of detection level
	Stored	0.01	0.04	
Cr, mg/kg (d)	Fresh	0.16	0.28	Unlikely to have operational impact
	Stored	0.22	0.73	
Co, mg/kg (d)	Fresh	0.22	0.19	Unlikely to have operational impact
	Stored	0.18	0.62	
Cu, mg/kg (d)	Fresh	3.81	4.92	Unlikely to have operational impact
	Stored	4.07	9.40	
Mo, mg/kg (d)	Fresh	0.09	0.09	Unlikely to have operational impact
	Stored	0.11	0.18	
Zn, mg/kg (d)	Fresh	79.4	97.1	Unlikely to have operational impact
	Stored	94.8	207.6	
Fe_2O_3, %wt (na)	Fresh	0.37	0.53	Unlikely to have operational impact
	Stored	0.44	1.38	
Fe, mg/kg (d)	Fresh	46.6	78.1	Unlikely to have operational impact
	Stored	56.2	290.3	

For willow leaves, only the impact of soil type could be assessed as all the sites were in a single climate zone and no storage was involved. Figure 6-4 provides an overview of the impact of this experimental factor on the characteristics of the leaves. The statistics suggest a number of characteristics are impacted by soil type. Closer inspection of the data reveals that a number can be disregarded, as the differences are within analytical repeatability or insufficient to be operationally significant (see Table 6-5). By contrast, the differences seen for nitrogen (dry), cadmium and lead are significant on all criteria (statistical, analytical and operational). The differences in nitrogen content from the leaf samples taken from medium and light soils are shown in Figure 6-3.

Table 6-4: Structured analysis of willow leaves

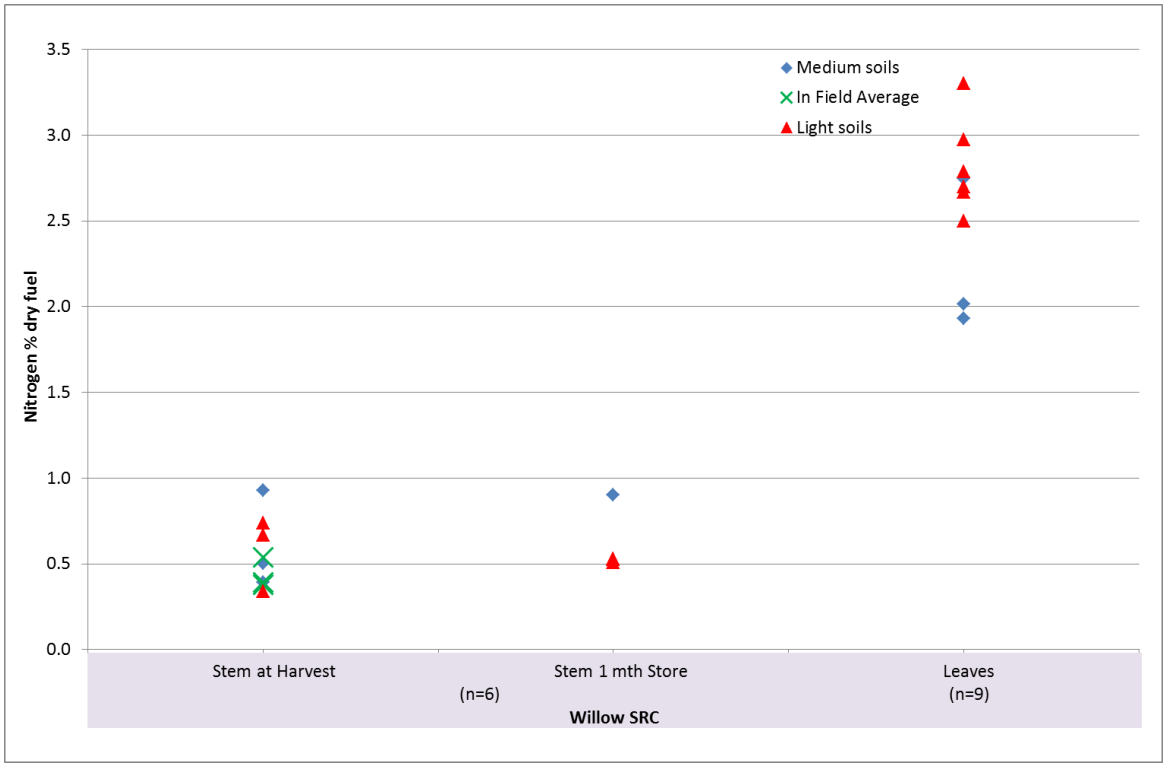
Variable†	SOIL TYPE
Moisture (ar)	0.775
Net calorific value (ar)	0.960
Ash content (d)	0.700
Volatile matter (DAF)	0.185
Gross calorific value (DAF)	0.063
Carbon (DAF)	0.906
Hydrogen (DAF)	0.000
Nitrogen (DAF)	0.013
Sulphur (DAF)	0.680
Chlorine (DAF)	0.488
Barium (d)	0.389
Chromium (d)	0.606
Cobalt (d)	0.969
Copper (d)	0.094
Molybdenum (d)	0.561
Nickel (d)	0.617
Vanadium (d)	0.176
Zinc (d)	0.537
Antimony (d)	0.910
Arsenic (d)	0.325
Mercury (d)	0.591
Bromine (d)	0.118
Cadmium (d)	0.020
Lead (d)	0.000
Al_2O_3 (na)	0.045
BaO (na)	0.517
$CaCO_3$ (na)	0.153
Fe_2O_3 (na)	0.345
K_2O (na)	0.365
MgO (na)	0.348
Mn_3O_4 (na)	0.129
Na_2O (na)	0.000
P_2O_5 (na)	0.454
SiO_2 (na)	0.141
TiO_2 (na)	0.136
Aluminium (d)	0.019
Calcium (d)	0.631
Iron (d)	0.307
Potassium (d)	0.138
Magnesium (d)	0.361
Manganese (d)	0.118
Sodium (d)	0.005
Phosphorous (d)	0.529
Silicon (d)	0.188
Titanium (d)	0.179
Alkali index	0.165

†basis of analysis; ar = as received fuel, d = dry fuel, DAF = dry, ash-free fuel, na= normalised ash. Dark blue cells indicate $p<0.001$; light blue cells $0.001<p<0.05$

Table 6-5: Mean values and assessment of relevance for main effects and interactions identified by structured analysis of willow leaves

Variable	Soil Type		Assessment
	Light	Medium	
Default number of analyses	6	3	
H, %wt (DAF)	6.53	6.33	Exclude – within repeatability of analysis
N, %wt (DAF)	3.06	2.43	Relevant for further study
Cd, mg/kg (d)	3.193	6.69	Relevant for further study
Pb, mg/kg (d)	0.495	1.439	Relevant for further study
Al_2O_3 %wt (na)	0.20	0.34	Unlikely to have operational impact
Na_2O %wt (na)	0.32	0.42	Unlikely to have operational impact
Al, mg/kg (d)	76.7	124.8	Unlikely to have operational impact
Na, mg/kg (d)	167.0	220.1	Unlikely to have operational impact

Figure 6-3: Results from the nitrogen analysis of willow SRC



Plots illustrating all the characteristics for willow are included in Appendix 10.

6.3 Null hypothesis

Of the many site properties collected for willow SRC, the following are suitable for statistical analysis: year of planting, age of sampled material, soil classification, pH and cation exchange capacity (CEC). In this section, the relationship between either the year of planting or the age of sampled material and feedstock characteristics is considered by correlation analysis, as discussed in Section 2.6.3. The impact of soil classification was investigated in the structured analysis, as presented in Section 6.2, and the impact of pH and CEC are covered in the soil-feedstock parameter correlation analysis, which is presented in Section 6.4.

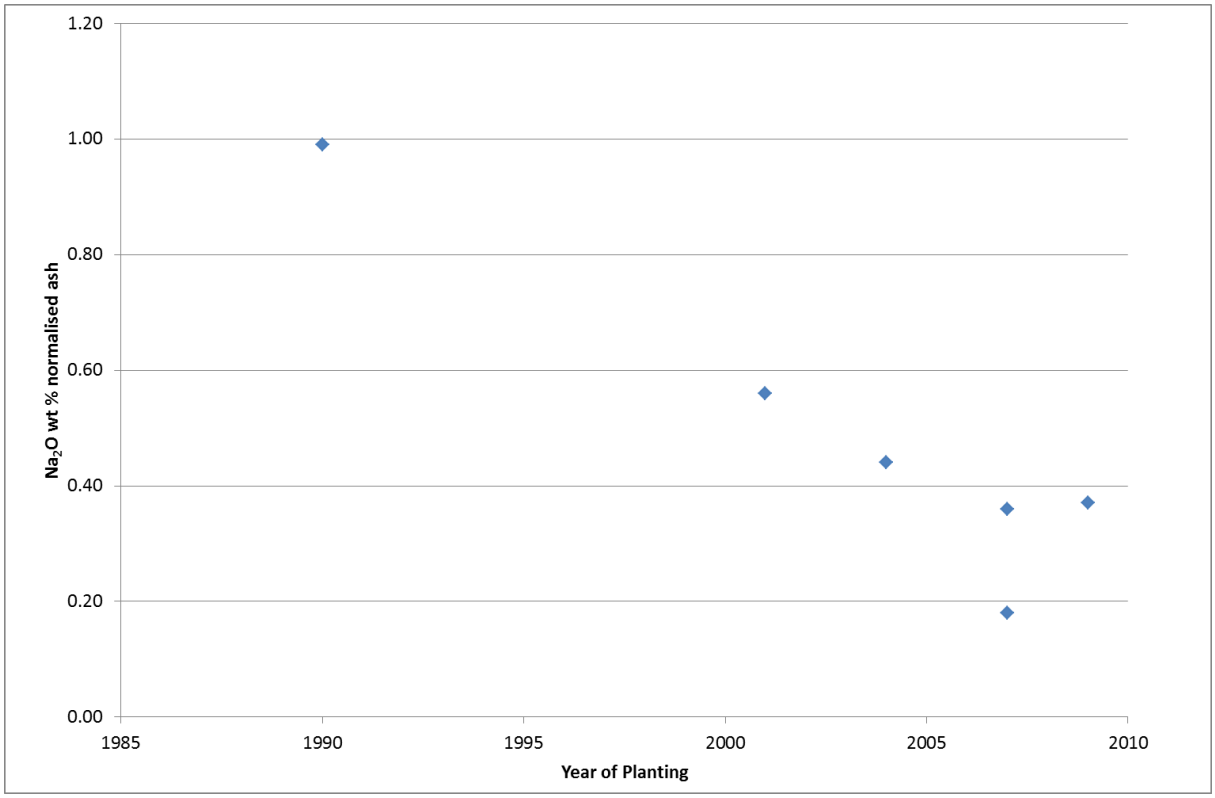
The full results of the correlation analysis are presented in Appendix 9, with the tables colour-coded to indicate those correlations (positive or negative) which explain either >50% or >80% of the variability, as discussed in Section 2.6.5. Table 6-6 presents an extract of this table, showing the strongest correlations.

Table 6-6: Regressions between selected provenance information and feedstock characteristics of fresh Willow SRC

Variable (basis)	Year of planting	Age of sampled stems
Carbon (DAF)	0.232	-0.853
Hydrogen (DAF)	-0.058	0.765
Nitrogen (DAF)	-0.087	-0.736
Sulphur (DAF)	0.735	-0.320
Antimony (d)	1.000	-0.500
Arsenic (d)	1.000	-0.500
Mercury (d)	-1.000	0.500
Bromine (d)	0.500	-1.000
$CaCO_3$ (na)	-0.029	0.883
K_2O (na)	0.319	-0.971
Na_2O (na)	-0.812	-0.177
Iron (d)	-0.087	-0.736
Potassium (d)	0.058	-0.883
Magnesium (d)	-0.232	-0.795
Sodium (d)	-0.754	-0.029
Phosphorous (d)	0.058	-0.883
Alkali index	0.058	-0.883

Year of planting was shown to be correlated with concentrations of S, Sb, As, Hg, Na and Na_2O in the willow, but with the exception of sodium and Na_2O in ash, the concentrations of these elements were at or below the limit of detection and so the data are unreliable. Looking more closely at sodium and Na_2O, a negative relationship with planting year can be seen (Figure 6-4), i.e. the more recently planted willow crops had lower concentrations of sodium in the dry fuel and Na_2O in the ash.

Figure 6-4: Correlation between Na_2O in willow SRC ash and year of planting



The age of the harvested material, which ranged from 2 to 4 years, had a greater number of meaningful relationships with feedstock characteristics than the year of planting, with relationships to proximate and ultimate analysis as well as elemental composition of the crop and the ash composition. Nitrogen appeared to decrease as the harvested willow increased in age, but there were relatively few data points so this finding should be viewed with caution. The relationships with carbon (negative) and hydrogen (positive), though interesting, were not operationally significant. K_2O in the ash, elemental Fe, K, Mg, P, and the Alkali Index all tended to decrease as the harvested willow increased in age, whereas $CaCO_3$ in the ash increased with crop age; these are all are operationally interesting but there are only a few data points so these findings should be viewed with caution.

6.4 Determining factors

Determining the factors of greatest importance to feedstock characteristics can only be done in a qualitative way by review of the statistical analyses performed. For willow SRC the structured factors were soil type and storage in Study 1 and soil type in Study 3. The other statistical analyses to be considered are the correlations with soil characteristics and the correlations with site information (where these were possible).

The statistics for willow SRC highlighted just one impact of soil type and a large number of impacts due to storage and interaction between soil type and storage but none were judged to be noteworthy (Table 6-3). Willow SRC leaves were significantly influenced by soil type in terms of nitrogen, lead and cadmium content (Table 6-5).

As discussed in Section 2.6.3, the total variation explained by these structured factors was quantified using REML; the result of this (for all feedstocks) is presented in Appendix 9. For the willow SRC leaves, 39 % of the total variation in nitrogen could be explained using the

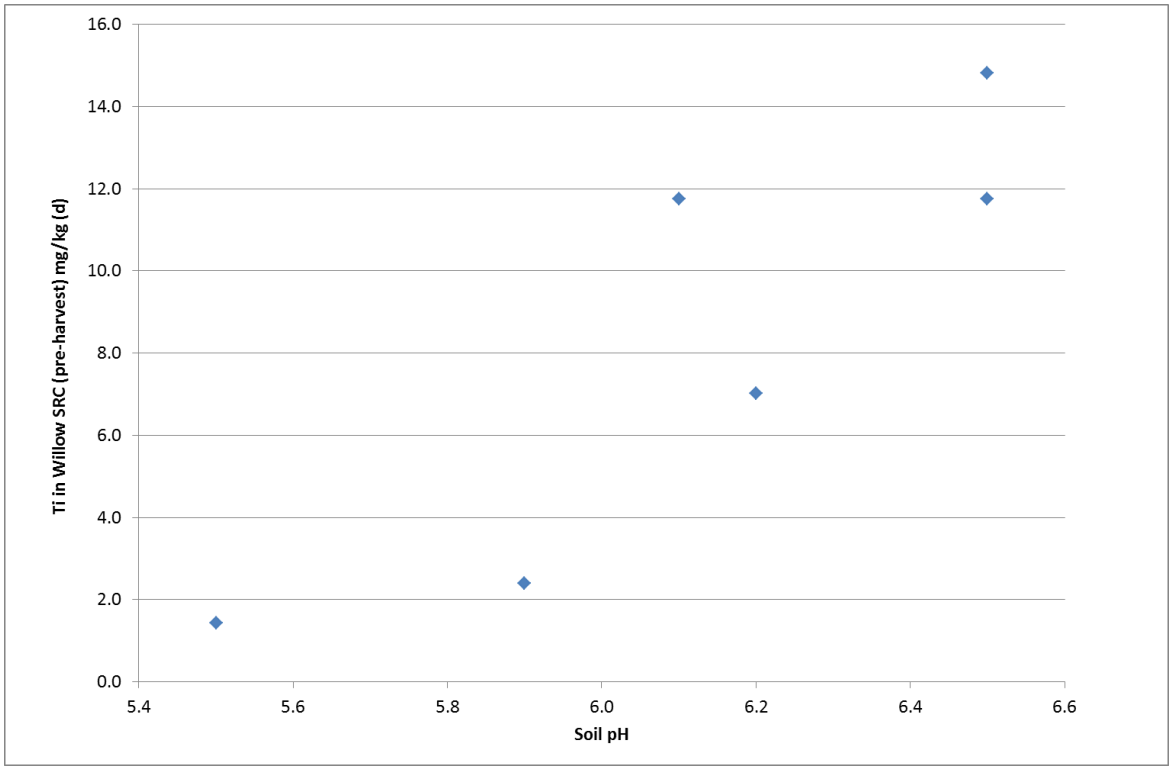
structured factor analysis, similarly 61 % and 36 % of the total variation in lead and cadmium was explainable.

Although general soil category did not appear to influence many feedstock parameters, there were numerous strong correlations between individual soil properties and feedstock characteristics (although the low number of sites should be noted). Statistical correlations between soil and feedstock parameters are shown in Appendix 5. All positive and negative correlations above +0.7 and below -0.7 have been highlighted, as in these cases the variation in soil properties explained just under 50% of the variation in feedstock characteristics, in either a positive or negative way. Any elements which were <LOD, within analytical repeatability levels, or simply deemed as not operationally significant have not been considered here.

As with the majority of sites in this project, the heavy metal content in the soils analysed for the willow SRC (whole plant and leaves sites in study 1, 2, and 3) were generally at the lower end of typical UK soil ranges (based on the Soil Guideline Values, published by the EA). However, the two leaf sampling sites (105 and 109) did show elevated heavy metal contents in the soil) - in particular for lead, cadmium, zinc and mercury - but this was not reflected in the leaves.

Levels of titanium in the willow SRC were not considered to be operationally significant, however this was one of the more interesting and strong correlations for willow SRC when correlated with soil pH. Although there are only six data points (so results should be interpreted with caution), a clear increase in titanium can be seen as the soil pH increases, see Figure 6-5.

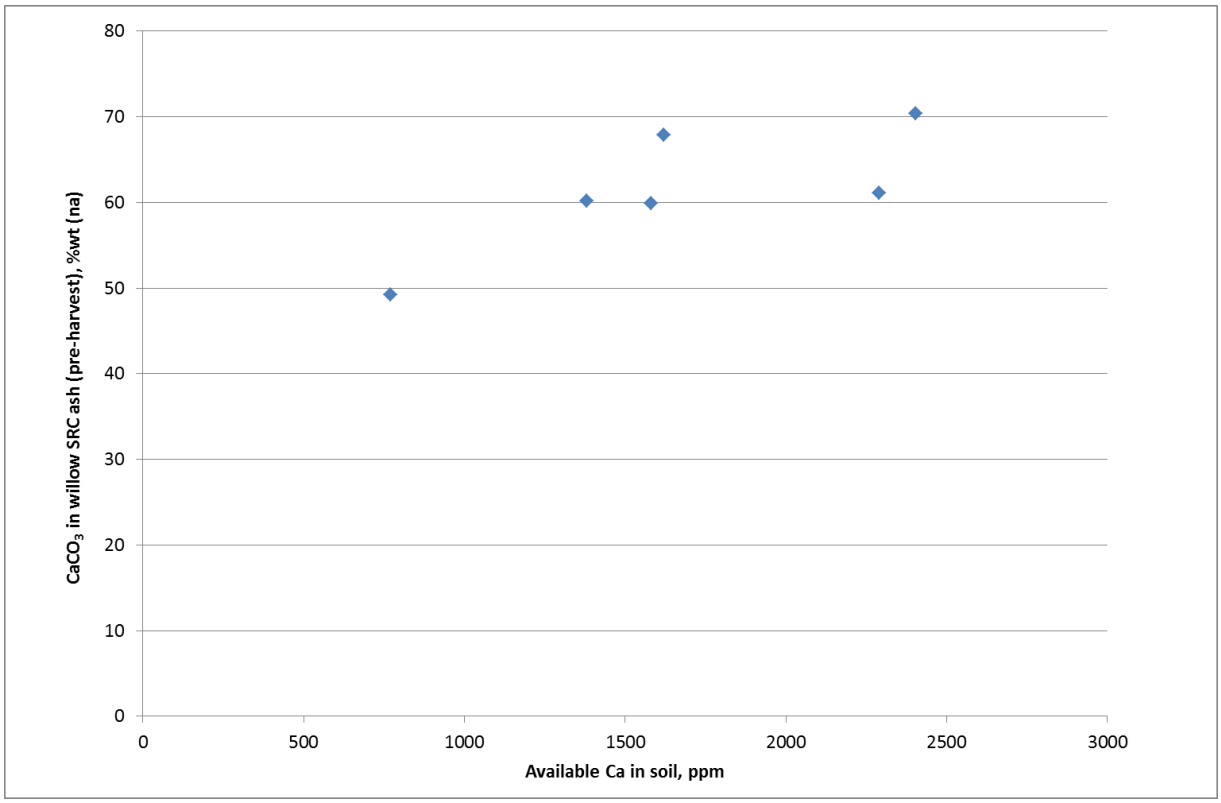
Figure 6-5: Correlation between soil pH and titanium in fresh willow SRC



The soil macroelement calcium showed a slight correlation with the $CaCO_3$ in the feedstock ash, one of only a few cases where there was a link between soil and feedstock concentrations of the same element. As the calcium level in the soil increased, the percentage level of $CaCO_3$

in the willow SRC ash increased, as seen in Figure 6-6. Soil calcium levels at the six willow SRC Study 1 sites were marginally lower than UK average soil types. This is also clearly reflected in the soil pH level and lime requirement for some of the willow sites.

Figure 6-6: Correlation between calcium in soil and $CaCO_3$ in normalised willow SRC ash



As calcium levels and soil pH can limit the availability of certain elements (see Figure 6-7), an understanding of their levels at the sites will help to estimate if the soil pH level has influenced the available elements for plant uptake.

Figure 6-7: Bioavailability of elements in soil with varying pH (from https://planetpermaculture.wordpress.com/)

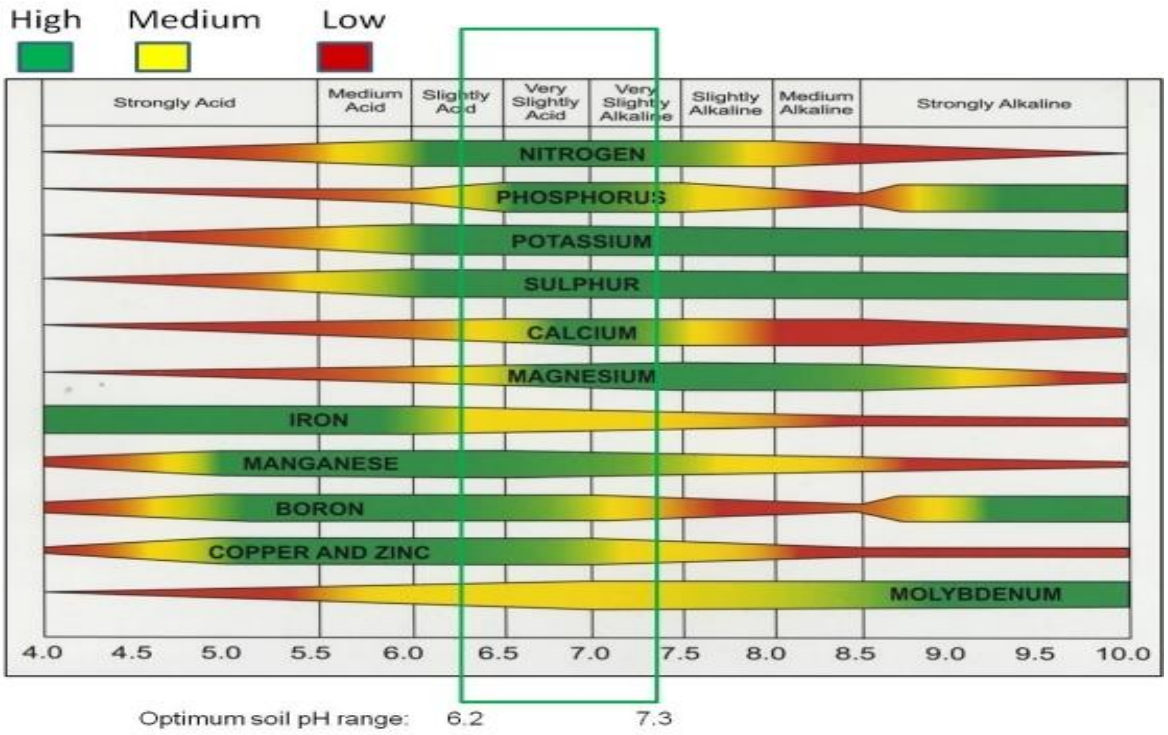
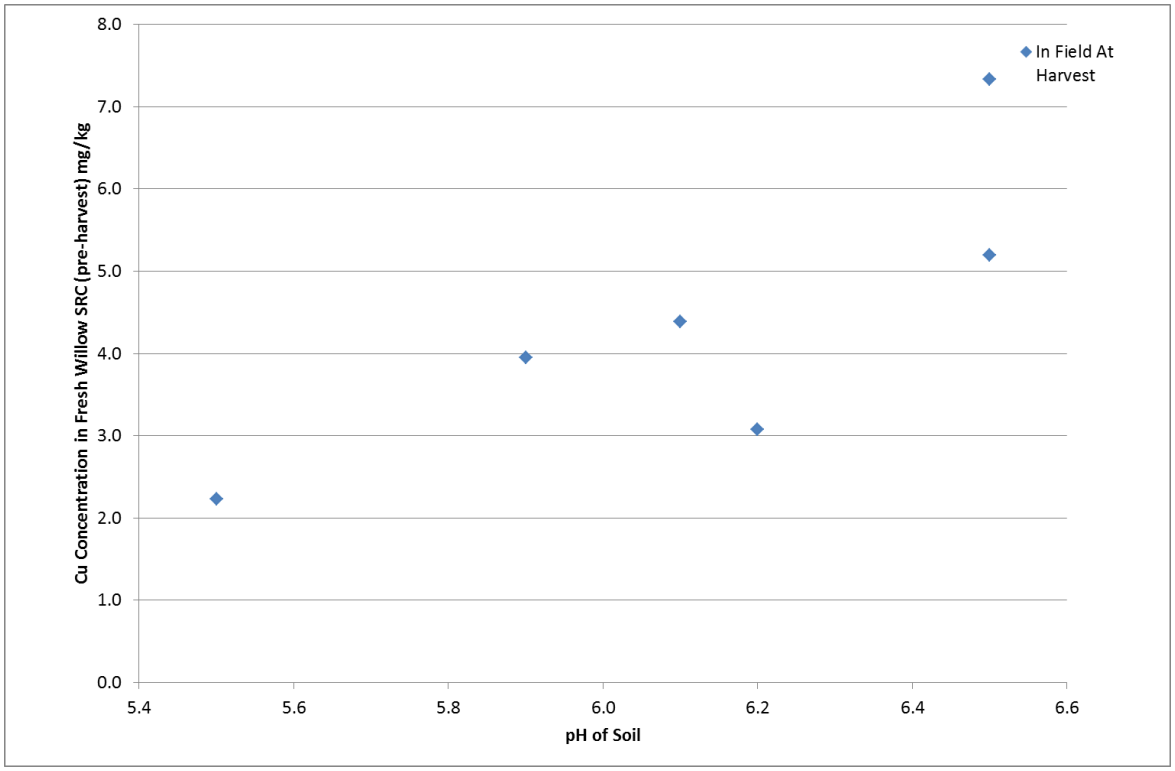


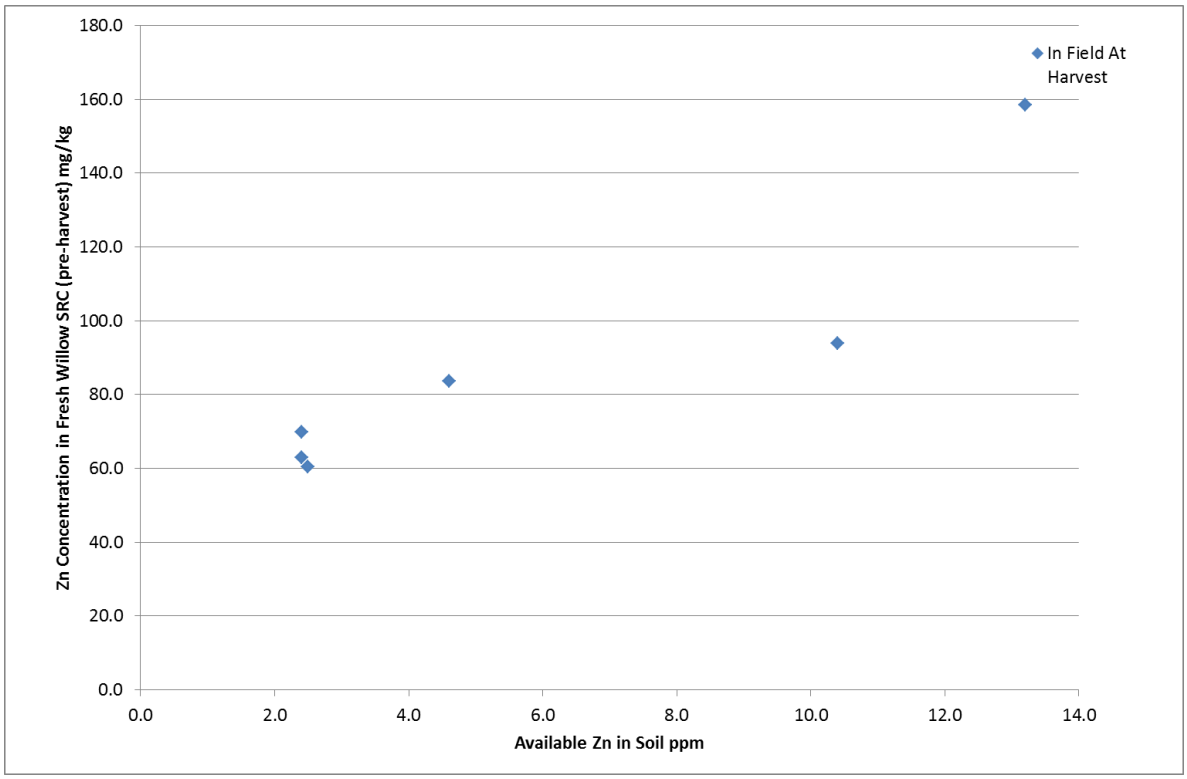
Figure 6-7 shows that when the soil pH drops below 6.5, becoming more acidic, the availability of some elements increases, notably for copper, zinc and manganese. Yet when looking at a correlation chart between copper in the willow SRC and soil pH, as shown in Figure 6-8, the level of copper appears to increase as the pH rises, contradicting the expected relationship between soil availability and feedstock concentrations. The copper levels found in the soils are well within UK agriculture averages, the typical range of UK soils being 2-100 ppm. Although copper availability decreases as organic matter in soil increases, no evidence of this was seen with regards to copper levels in willow stem samples.

Figure 6-8: Relationship between copper in fresh willow feedstocks and soil pH



Like calcium, the zinc concentration in the soils shows a reasonable correlation with zinc in the feedstock for fresh willow SRC, although the small data set must be taken in to consideration. Levels in the feedstock ranged from 60.8-158.4 mg/kg, whilst the bioavailable soil zinc levels increased from 2.4 to 13.2 ppm (see Figure 6-9).

Figure 6-9: Relationship between zinc levels in fresh willow SRC and bioavailable zinc in soil



In September, willow SRC leaves were collected from nine different sites, with only three sites out of the nine having been visited previously for whole plant material samples. There were considerably more correlations between willow SRC leaf composition and soil composition than for the fresh willow SRC material. However, a review of these willow SRC leaf correlations showed the majority to be either <LOD, within analytical repeatability, or not operationally significant.

The soil type for the willow SRC leaves were predominantly light soils, with only three classed as medium soils. Two of the nine sites were classed as being Organic soils with over 6% organic matter content. As with the analysis of correlations between stem material and their corresponding soil, there were no correlations identified between the organic matter content and any of the leaf feedstock components. The only slight correlation found was between the percentage of organic matter content in the soil and the level of the ash oxide $CaCO_3$ in the feedstock, but it is inconclusive having only six data points.

Similarly to the zinc correlation in the whole plant (Figure 6-9) the willow SRC leaves also showed a good correlation between the zinc in the leaves and zinc in the soil, see Figure 6-10. However the limited data set should always be considered, before drawing too many conclusions from the results.

Figure 6-10: Relationship between zinc in willow SRC leaves and available zinc in soil

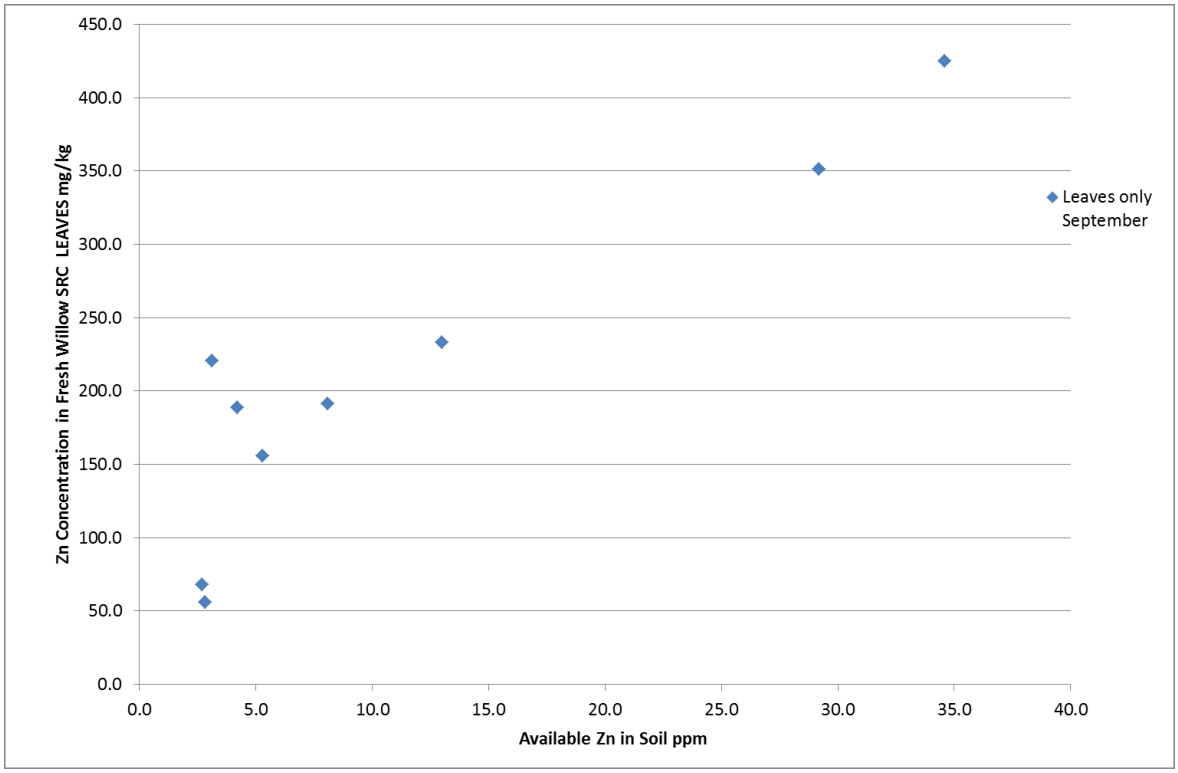
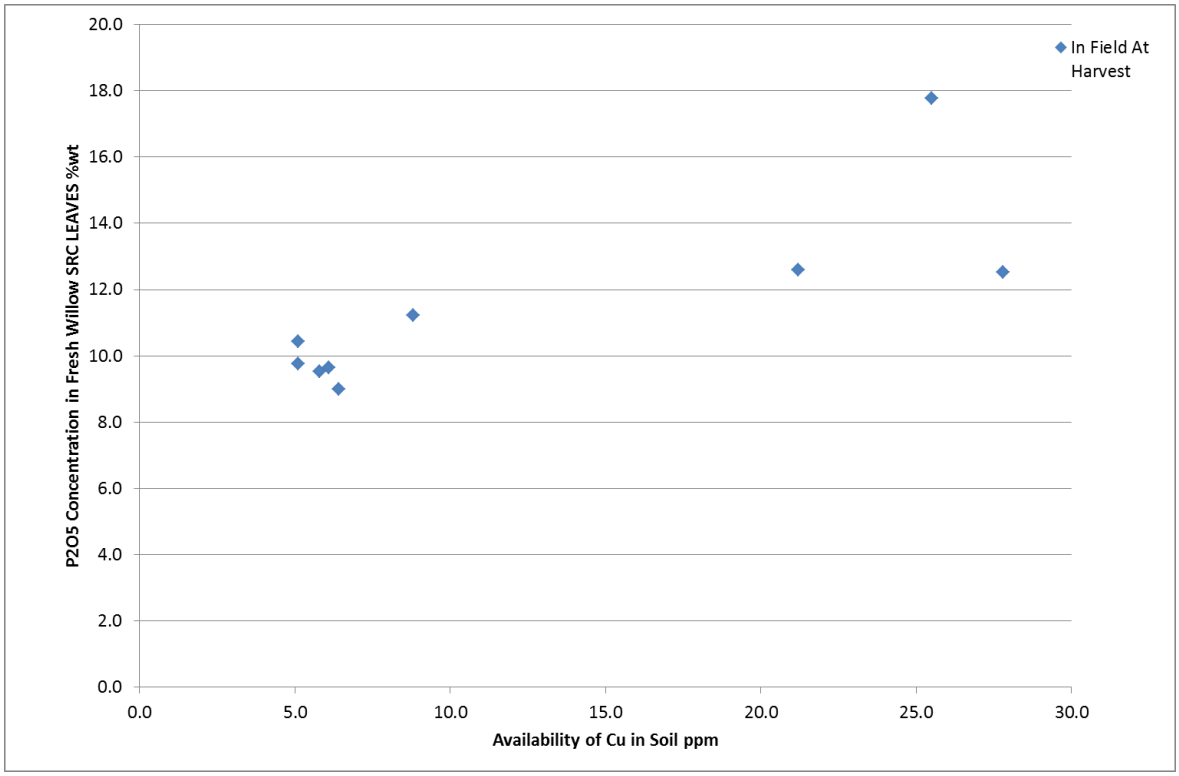


Figure 6-11 shows a reasonable correlation between copper in the soil and the percentage of oxide P_2O_5 in the ash.

Figure 6-11: Relationship between P_2O_5 levels in ash for willow leaves SRC and available copper in soil



Management factors had a limited influence: sodium and Na_2O of the willow SRC were negatively related with planting year; nitrogen, K_2O in the ash, elemental Fe, K, Mg, P, and the Alkali Index all tended to decrease as the harvested willow increased in age whereas $CaCO_3$ in the ash increased with crop age.

Although two of the sites were identified as having had sewage sludge applied, Table 6-7 shows that the trace element levels within their soils were equivalent, or lower, than those of the untreated willow sites. It should be noted that all applications were more than 10 years before this exercise. No data on the sewage sludge composition was available.

Table 6-7: Comparison of total soil trace element content for willow SRC sites with and without sewage sludge treatment

	Element	Cu	Zn	Pb	As	Cd	Hg	Cr
Sewage sludge treated sites	Total concentration in dry soil / Site number	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	016	8.44	35.27	15.29	5.29	0.06	0.01	12.68
	104	21.51	51.98	19.74	7.00	0.07	0.1	23.66
Average sludge treated soils		14.98	43.63	17.52	6.15	0.065	0.055	18.17
Average non-sludge treated soils		22.85	86.11	50.21	7.80	0.33	0.32	35.11

The various influences described above have been collated, focussed on the variables thought in the team's expert opinion to be important in a commercial operational context, and ranked in a qualitative way. Table 6-8 must be treated with caution especially because of the relatively small number of sites investigated but nevertheless indicates that feedstock characteristics

are not affected in a consistent way by the site properties and crop management. These results imply that the grower has a reasonable degree of control over some of the important feedstock characteristics by his/her choice of harvesting time – as a means of controlling leaf content – the age of the root stock and the length of the cutting cycle. The implications for buyers are that consideration must be given to the feedstock characteristics of prime importance in a particular application.

Table 6-8: Factors influencing key feedstock characteristics of Willow SRC ranked in order of decreasing importance.

Variable	Rank 1	Rank 2	Rank 3
N, %wt (DAF)	Plant part	Soil type	Crop age
Cd, mg/kg (d)	Plant part	Soil type	
Pb, mg/kg (d)	Soil type	Plant part	
Na_2O, %wt (na)	Planting year		
Na, mg/kg (d)	Planting year		
K_2O, %wt (na)	Crop age		
P, mg/kg (d)	Crop age		
Alkali Index	Crop age		
K, mg/kg (d)	Crop age		
Mg, mg/kg (d)	Crop age		
Iron, mg/kg (d)	Crop age		

6.5 In-field variation

At each of the three in-field variation sites, 20 biomass samples were collected from across the field and analysed separately, which allowed the variability within each field to be investigated. The locations of sampling points within each site are shown in Figure 6-12 to Figure 6-14, with the profile graph showing the change in elevation (metres above sea level) along the route from point 1 to 20. Table 6-9 shows the average values and the coefficient of variance for each set of in-field data; it also compares the variance with and between sites to the overall variance. As in Section 5.5, this table has been shaded to indicate for which parameters the variance between the sites was higher than the variance within the site and vice versa.

Figure 6-12: Site map for willow SRC IFV1 (site 046)

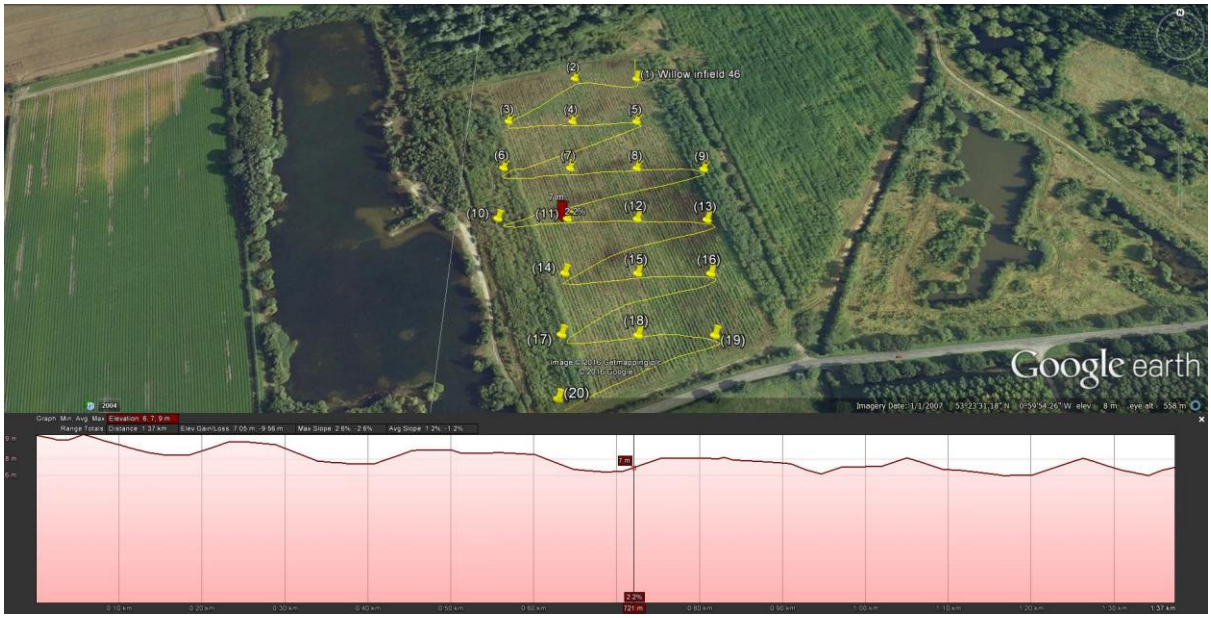


Figure 6-13: Site map for willow SRC IFV2 (site 047)

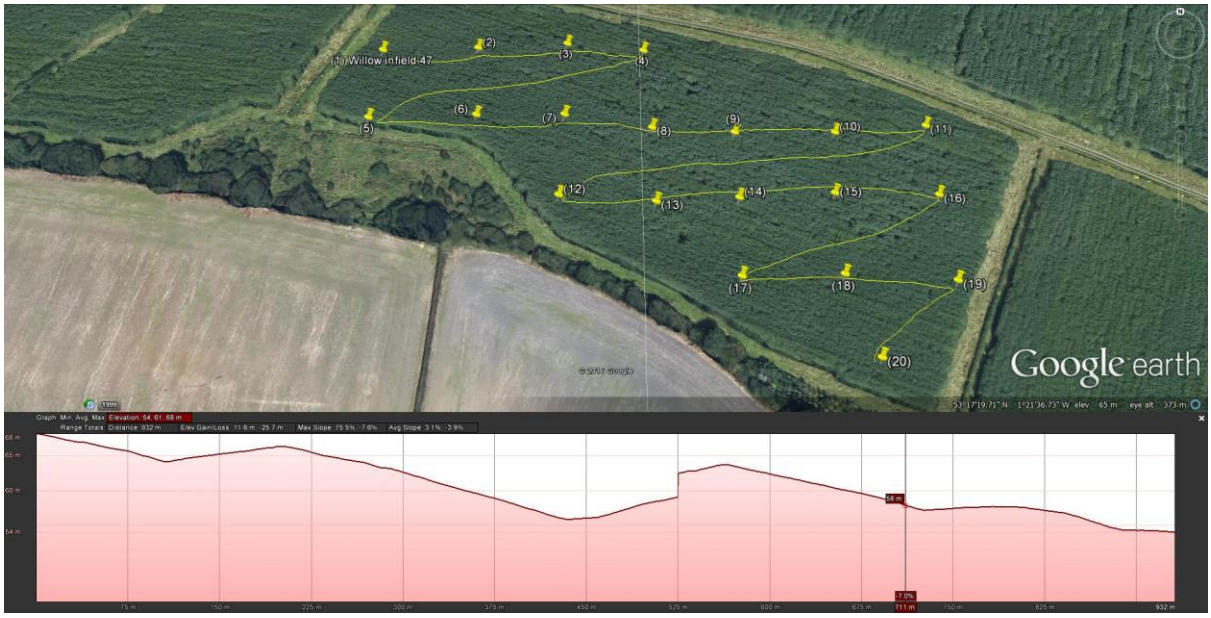


Figure 6-14: Site map for willow SRC IFV3 (site 048)

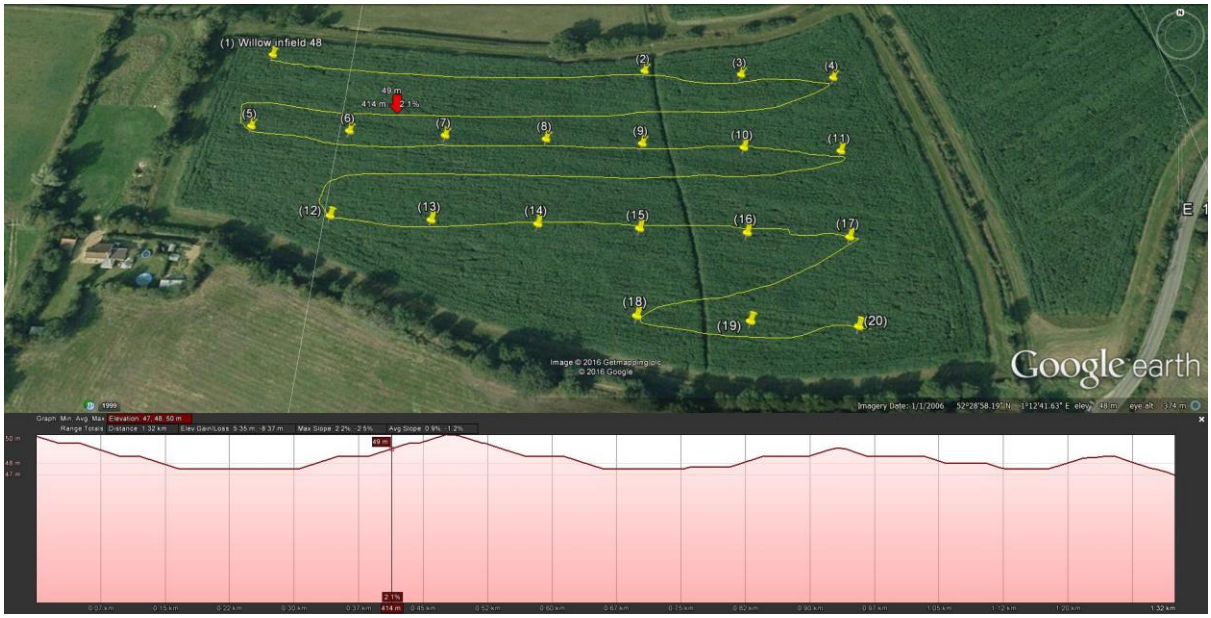


Table 6-9: Variance of willow SRC in-field sampling sites

	IFV 1		IFV 2		IFV 3		Variance between sites relative to total variance (%)	Variance within sites relative to total variance (%)
Variable	Mean	Coefficient of Variance %	Mean	Coefficient of Variance %	Mean	Coefficient of Variance %		
Moisture (ar)	52.3	2.61	51.4	2.25	55.6	1.83	77.9	22.1
Net calorific value (ar)	7462	3.57	7641	3.19	6751	3.12	79.0	21.0
Ash content (d)	1.3	16.96	1.6	9.97	1.7	8.72	49.9	50.1
Volatile matter (DAF)	84.0	0.5	84.0	0.42	84.1	0.47	0.0	100.0
Gross calorific value (DAF)	19904	0.69	19940	0.57	19973	0.26	0.0	100.0
Carbon (DAF)	50.42	0.79	50.39	0.66	49.87	0.74	40.4	59.6
Hydrogen (DAF)	6.18	1.04	6.14	0.51	6.19	1.4	12.7	87.3
Nitrogen (DAF)	0.38	13.23	0.54	13.68	0.39	17.99	64.0	36.0
Sulphur (DAF)							*	*
Chlorine (DAF)	0.01	57.29	0.01	37.38	0.01	0	9.9	90.1
Barium (d)	52.29	28.31	9.04	28.51	3.04	22.47	90.5	9.5
Chromium (d)	0.18	22.35	0.28	26.32	0.11	13.84	20.9	79.1
Cobalt (d)	0.33	35.79	0.14	34.01	0.12	18.25	65.4	34.6
Copper (d)	3.61	10.44	4.79	9.73	3.76	10.68	6.5	93.5
Molybdenum (d)	0.08	15.53	0.09	9.72	0.10	9.48	4.7	95.3
Nickel (d)	0.41	35.4	1.19	35.07	0.50	27.2	0.0	100.0
Vanadium (d)	0.09	26.08	0.14	51.05	0.10	10.05	17.2	82.8
Zinc (d)	88.67	16.98	99.55	13.86	52.63	9.71	6.5	93.5
Antimony (d)							3.3	96.7
Arsenic (d)							25.9	74.1
Mercury (d)							8.6	91.4
Bromine (d)							3.5	96.5
Cadmium (d)	1.5	56.49	1.43	30.54	1.58	57.42	0.0	100.0
Lead (d)	0.73	82.08	0.39	32.81	0.16	53.79	6.0	94.0
Al_2O_3 (na)	0.18	16.19	0.9	70.19	0.11	48.88	47.1	52.9
BaO (na)	0.39	29.63	0.05	27.87	0.02	33.34	90.2	9.9

	IFV 1		IFV 2		IFV 3		Variance between sites relative to total variance (%)	Variance within sites relative to total variance (%)
Variable	Mean	Coefficient of Variance %	Mean	Coefficient of Variance %	Mean	Coefficient of Variance %		
$CaCO_3$ (na)	61.52	7.73	60.25	7.39	76.68	2.85	84.0	16.0
Fe_2O_3 (na)	0.3	27.22	0.46	47.6	0.12	10.34	5.3	94.7
K_2O (na)	17.41	14.68	16.54	11.58	11.85	7.71	70.4	29.6
MgO (na)	5.77	16.47	4.16	6.61	2.19	9.57	90.4	9.6
Mn_3O_4 (na)	1.11	41.61	0.16	34.13	0.34	54.99	74.8	25.2
Na_2O (na)	0.49	16.2	0.33	14.62	0.28	15.61	56.3	43.7
P_2O_5 (na)	11.27	15.39	11.91	8.81	7.64	11.07	76.4	23.6
SiO_2 (na)	1.16	29.8	3.73	59.53	0.76	24.99	47.5	52.5
TiO_2 (na)	0.07	44.77	0.12	29.71	0.01	1.29	22.6	77.4
Aluminium (d)							46.8	53.2
Calcium (d)							73.6	26.4
Iron (d)							4.4	95.6
Potassium (d)							54.6	45.5
Magnesium (d)							87.4	12.7
Manganese (d)							67.8	32.2
Sodium (d)							23.3	76.8
Phosphorous (d)							76.6	23.4
Silicon (d)							47.9	52.1
Titanium (d)							31.6	68.4
Alkali index							54.1	45.9

Pink shaded cells indicate where over 66% of the total variance was either between sites or within sites

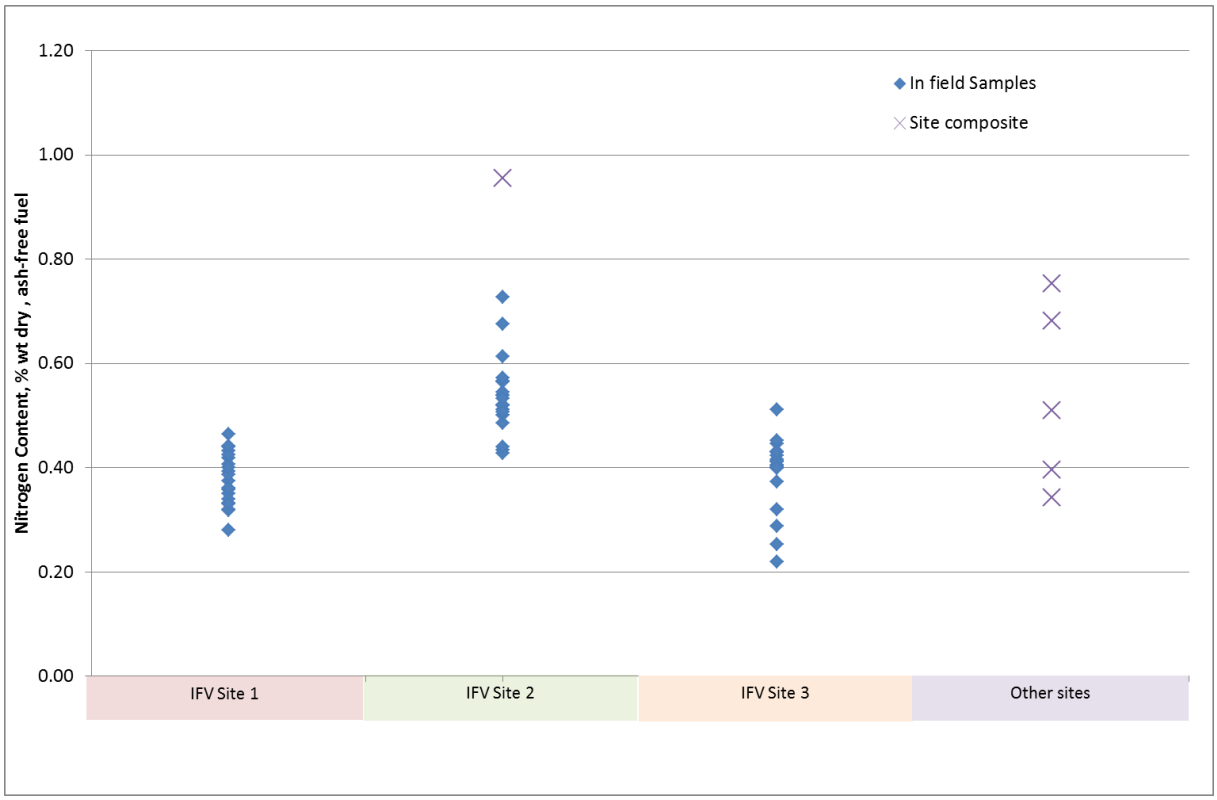
Comparing the variance in feedstock characteristics from site to site versus within field, it is clear from Table 6-9 that for some feedstock characteristics there was greater variation from site to site than within-field, for example moisture, net CV and manganese. For other characteristics (e.g. ash % and aluminium) the variation was much the same within-field and between different sites. Finally, for others (e.g. chlorine and many trace elements) the variation within-field was much greater than the variation between sites.

In contrast to the *Miscanthus*, the variation of moisture content of willow stems between sites was significantly less, Figure 6-15 illustrates the consistent behaviour across the three in-field sites.

Figure 6-15: Results from the moisture analysis of willow for in-field variation sites of Study 2 (study 1 values also provided for comparison)

The nitrogen content in the willow SRC is shown in Figure 6-16. It should be noted that the chlorine content in all the willow samples was so low as to be less than the limit of detection.

Figure 6-16: Results from the nitrogen analysis of willow SRC for in-field variation sites of Study 2 (study 1 values also provided for comparison)



In terms of trace and macro elements, again the behaviour of barium was striking (see Figure 6-17), with the willow SRC samples from in-field variation site 1 showing very high and variable concentrations compared to the other sites. Unfortunately no soil samples were analysed for barium, so the cause of this behaviour could not be traced. Cobalt was also notably higher in willow SRC IFV site 1 – this is almost certainly due to the cobalt concentration in the soils, which was highest in IFV site 1 and lowest in IFV site 3 – see Figure 6-18.

Figure 6-17: Results from the barium analysis of willow for in-field variation sites of Study 2 (study 1 values also provided for comparison)

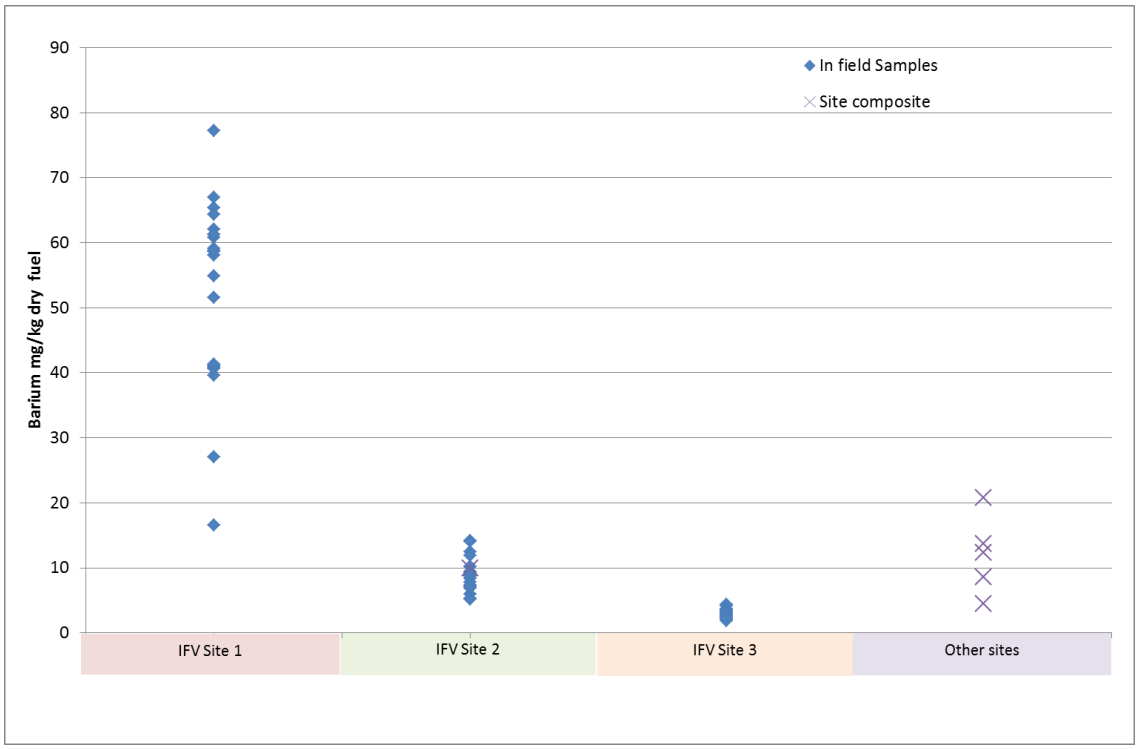
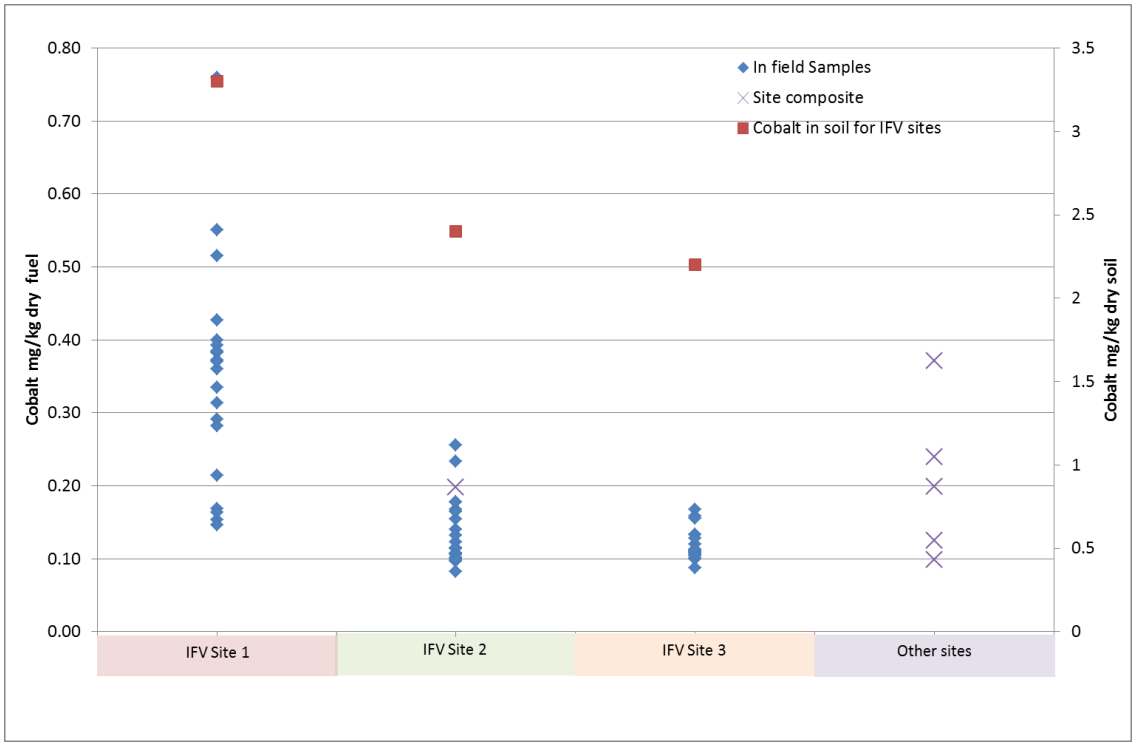
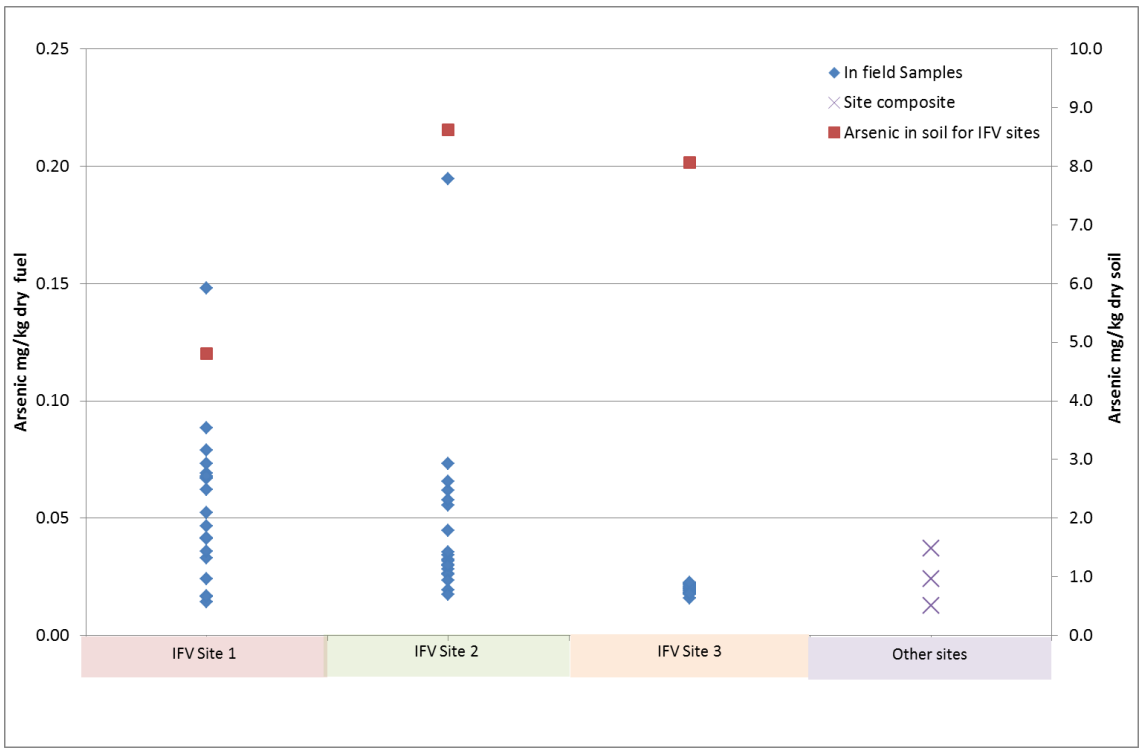


Figure 6-18 Results from the cobalt analysis of willow SRC for in-field variation sites of Study 2 (study 1 values and IFV soil analysis also provided for comparison)



Arsenic shows interesting behaviour, with the samples from IFV sites 1 and 2 showing higher and more variable concentrations than IFV3 (see Figure 6-19). The data obtained from IFV site 3 is surprisingly clustered. Unlike the data for cobalt, these data could not be reconciled with the arsenic concentrations determined in the soil samples.

Figure 6-19: Results from the arsenic analysis of willow SRC for in-field variation sites of Study 2 (study 1 values and IFV soil analysis also provided for comparison)

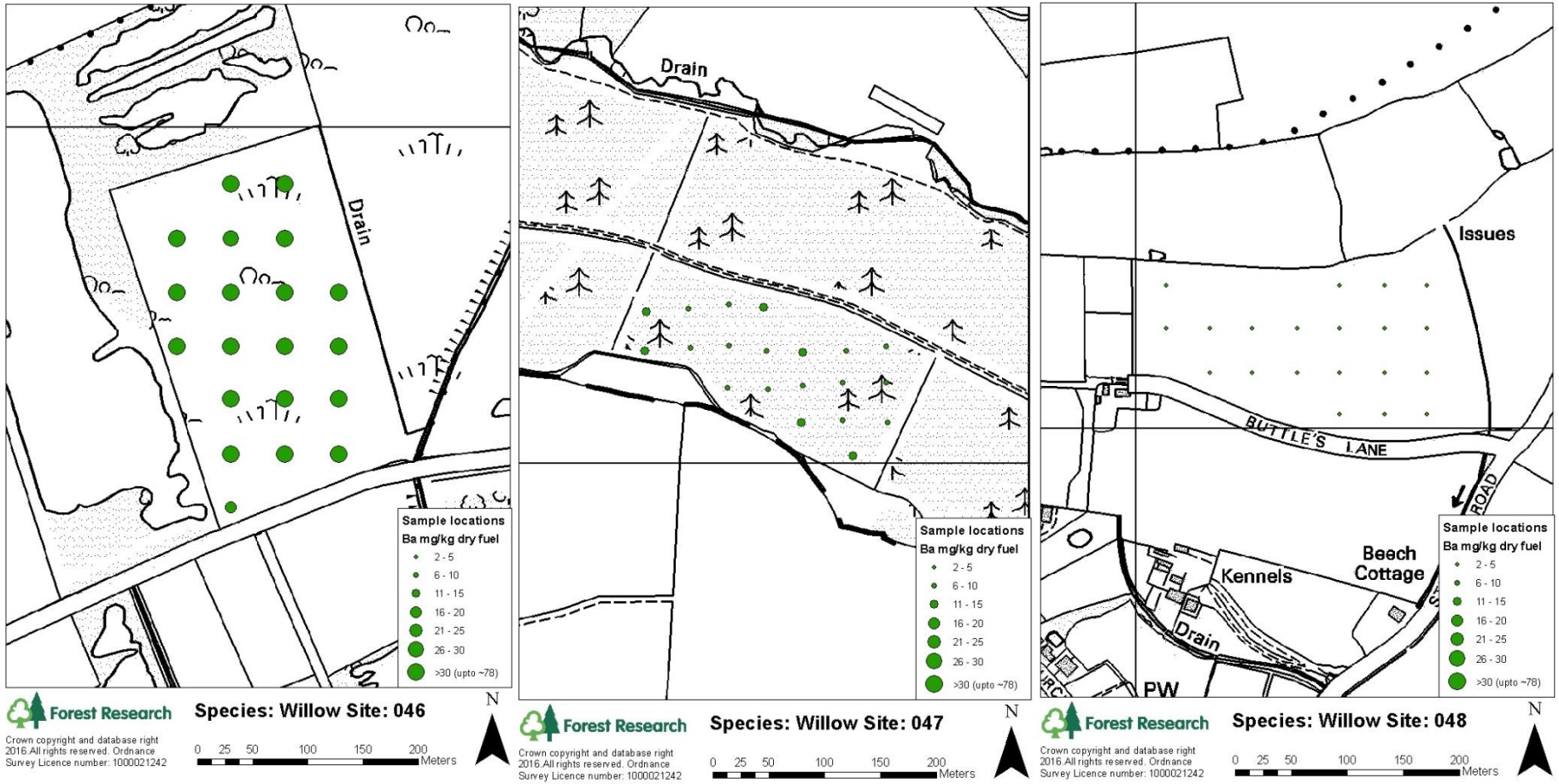


Other fuel parameters for willow SRC which showed a notable variation between the in-field sites included: aluminium, calcium, magnesium, phosphorous, silicon and titanium (plots of all the feedstock characteristics are shown in Appendix 10).

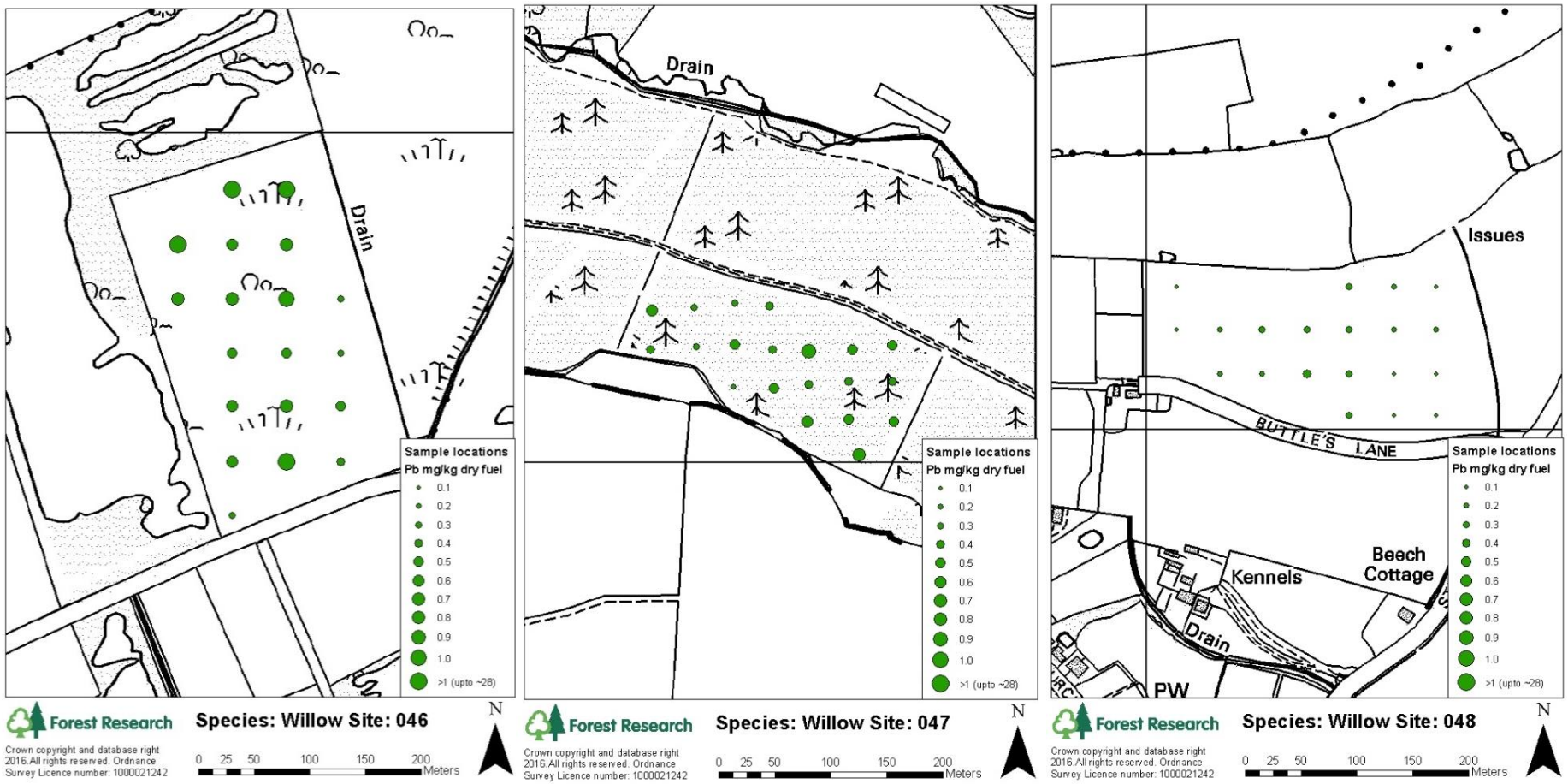
In order to visualise the variability of characteristics within each field, the sampling points at each site were plotted using the recorded sampling coordinates. For selected parameters (particularly those with high coefficients of variance), these location markers were then scaled to represent the magnitude of the analysis results. Examples of the resultant plots for barium (high variability between sites) and lead (high variability within site) are shown in Figure 6-20, with further examples in Appendix 4. Provenance information, including soil and air temperature at the time of sample collection, has also been plotted.

Figure 6-20: Concentrations of (a) barium and (b) lead in fuel samples taken at different in-field sites (Site 046 = IFV1, Site 047 = IFV2, Site 048 = IFV3)

a)



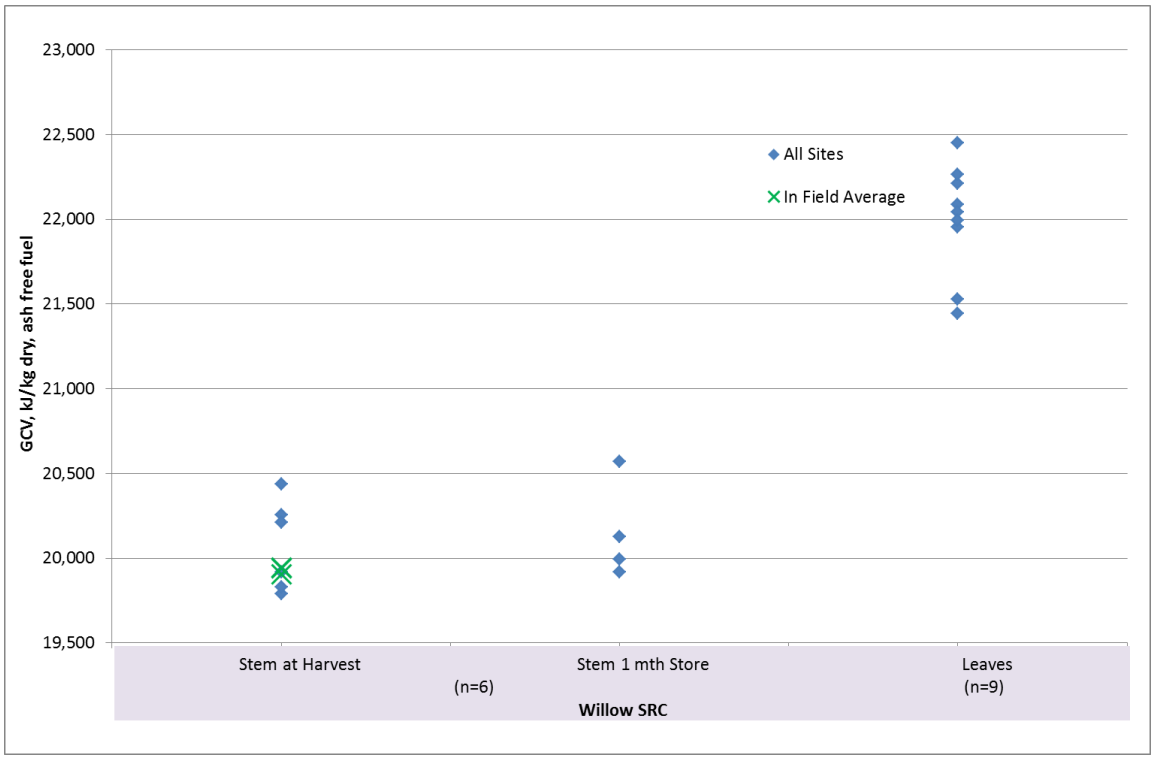
b)


Drain
Sample locations
Pb mg/kg dry fuel
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
>1 (upto ~28)
Forest Research
Species: Willow Site: 046
Crown copyright and database right 2016.All rights reserved. Ordnance Survey Licence number: 1000021242
0 25 50 100 150 200 Meters
N
Drain
Forest Research
Species: Willow Site: 047
Issues
BUTTLE'S LANE
Kennels
Beech Cottage
Drain
PW
Forest Research
Species: Willow Site: 048

6.6 Comparison of leaves vs whole plant

Leaf samples were taken from nine different sites, although not at the same time as the main willow SRC samples were taken. Figure 6-2 has already demonstrated that the moisture content of the leaves was similar to the willow SRC samples themselves. However, other chemical characteristics of the leaves were markedly different from the willow SRC, including DAF Gross CV – see Figure 6-21. This increase is due to the higher DAF carbon and hydrogen content (and hence lower oxygen content) of the leaves compared to the woody material, which also reduces their DAF VM content. However, due to the higher ash content of the leaves, their Net CV is reduced to be broadly similar to the willow SRC samples (Figure 4-4).

Figure 6-21 Results from the GCV (DAF) analysis of willow SRC in study 1 & 3, with average values for study 2 sites



In general, the graphs indicate that concentrations of most chemical parameters were higher in the leaves than the willow SRC samples. The higher ash content of the leaves compared to the willow SRC (approximately a 4-fold increase) will result in higher mineral and trace element concentrations. Figure 6-3 has previously illustrated the increased nitrogen content of the leaves at approximately 2.5 % (dry) compared to the willow SRC (approximately 0.5 % (dry)). It is worth noting that sulphur was virtually undetectable in the willow SRC, with concentrations in the leaves being approximately 0.5 % (dry); similar behaviour was observed for bromine which was detected in the leaves at approximately 20 mg/kg (dry), The behaviour of the macroelements in the leaves is interesting to note, with aluminium, iron, silicon and titanium only slightly elevated in the leaves compared to the willow SRC, but with the majority of the alkali and alkaline earth elements, plus phosphorous, present at significantly higher levels. Appendix 10 contains plots illustrating the changes in concentration of all the different characteristics in the willow (fresh and stored) and the leaves.

6.7 Conclusions and hypotheses

Relevant hypotheses

- *With the exception of Miscanthus, the feedstocks are differentiated into plant parts that have different functions, e.g. mechanical support versus photosynthesis; therefore we hypothesise that these plant parts will differ in their fuel properties and/or composition.* The composition of willow SRC leaves and willow SRC did differ, as discussed in Section 6.6.
- *Feedstock properties will differ depending on the climate the crop is exposed to*. There were not enough samples to test this.
- *Feedstock properties will differ depending on the soil composition and characteristics of the site.* The impact of soil type and composition was very limited and in only a very few instances was there a direct link between levels of a particular element in the soil and biomass. Although the number of data points was limited and the following associations have to be treated with caution, titanium and copper in the feedstock were positively related to soil pH, $CaCO_3$ in the feedstock ash was positively related to the available soil Ca, and zinc in both the stems and leaves was positively related to available zinc in the soil. The soil analysis data revealed that the sites were very 'clean', with below average or very low levels of soil metals and metalloids, which probably explains the absence of any impact of soil type and the very small number of strong correlations found between feedstock ash characteristics and soil properties. Willow SRC leaves tended to have the strongest correlation between feedstock ash characteristics and the soil composition; this could be due to the fact that several of their soils had considerably higher heavy metal levels than the other sites, being at or just above the UK average.
- *Feedstock properties will differ with storage.* Storage was important in a statistical sense but on the basis of analytical and operational criteria none of the impacts were judged to be worth following up.
- *Within a given field, feedstock properties will be relatively uniform.* There is no simple conclusion regarding the variation within fields compared to the variation between fields. For some feedstock characteristics there was greater variation from site to site than within-field, for example moisture, net CV and manganese. For others (e.g. chlorine and many trace elements) the variation within-field was much greater than the variation between sites. The pattern of variation may be related to past fertiliser additions, the relative abundance of the element, and the mobility of the element in its normal form in the soil.

Although relatively few sites were sampled during this project, and these did not represent the full range of climate and soil types where willow SRC is grown, some interesting results were still obtained.

- One month storage appeared to have no effect on moisture content, but longer storage times are typically used in commercial practice.

- Willow SRC leaves are more likely to be affected by soil type than the willow SRC. The most operationally relevant impact was on nitrogen concentration in the willow SRC leaves.
- A qualitative ranking of factors affecting the characteristics of willow SRC implies that the grower has a reasonable degree of control over some of the important feedstock characteristics by their choice of harvesting time (leaf content should generally be minimised e.g. by harvesting during the dormant period), the age of the root stock and the length of the cutting cycle.

Concentrations of most trace elements were higher in the willow SRC leaves than in the willow SRC stems. While several sites reported that sewage sludge had been applied, details of this were limited. None of the sites that reported receiving sludge showed elevated levels of heavy metals in either the soil or the biomass samples, which may seem unusual, but may be explained by the fact that all of the applications took place more than 10 years ago.

7 Poplar SRC

7.1 Introduction

Poplar (*Populus spp.)*, has many different varieties and natural hybrids, including ones that are single stemmed (where there is strong apical dominance), or multiple stemmed (like willow). The single stemmed hybrid varieties are becoming more common place and are of greater interest for dedicated SRF biomass energy production, with a harvest cycle of 12-25 years.

Poplar SRC is becoming a common choice in mainland Europe for dedicated biomass supply options, due largely to the rapid growth and high yields obtainable in a relatively short timeframe, whilst being more frost tolerant than *Miscanthus* and currently more disease resistant than willow SRC varieties. However, it has not really taken off in the UK as a dedicated energy crop, having not received initial planting grant support (unlike willow SRC and *Miscanthus*). As a result, few commercial sites could be found for sample collection.

Poplar SRC does benefit from fertiliser applications and yields can be seen to reflect application of nitrogen and phosphate in particular. Poplar SRC varieties typically prefer moist light soils, and if summer rainfall levels are low then yield and growth can quickly become inhibited. It is not as reliant on water availability as willow SRC, but is more reliant than *Miscanthus*. Typical mainland Europe yields are 15 ODT/ha/yr from the second cycle onwards, which makes it competitive with *Miscanthus* and marginally ahead of typical UK willow SRC yields.

Poplars can be found most commonly in the Northern Hemisphere areas of North America, Europe and Asia. The bark on the tree is usually smooth, and ranges from off white to a greenish dark grey in colour. Height ranges for the species can vary significantly from 8-50 m, depending on the variety, location and end use. If the tree is being harvested for a biomass end use on a 2-5 year harvesting cycle, for up to 6 harvest cycles, then 12-30 years of harvestable growth is achievable. For dedicated biomass production, the target harvesting stem/trunk diameters will be less than 20 cm (at 20-30 cm above ground level) with 15 cm being the targeted maximum for direct chipping machine operations.

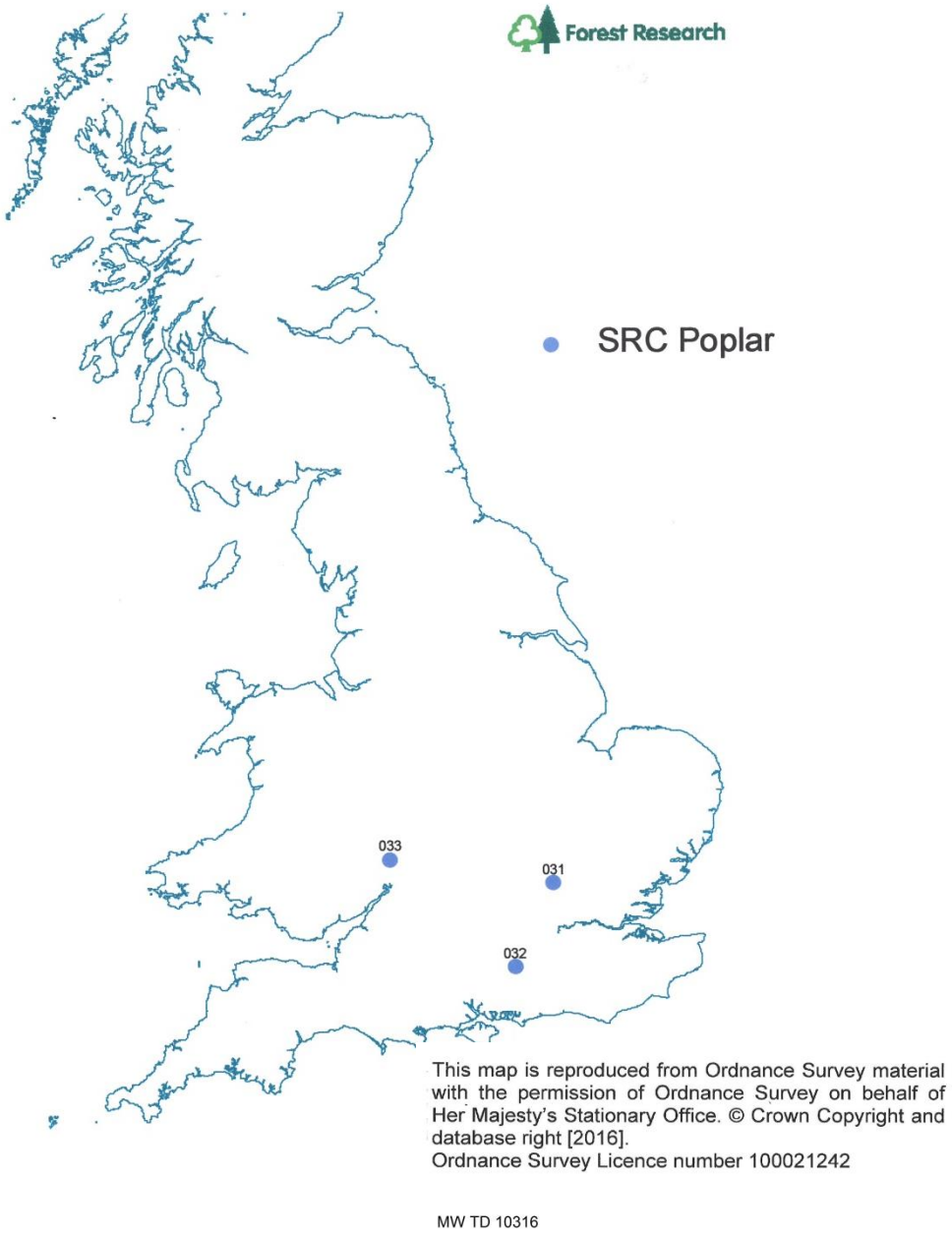
Dedicated poplar biomass plantations are generally established in the spring, at planting rates ranging between 1,500-15,000 cuttings/ha (depending on cycle of harvesting). There are different types of initial planting material used: poles or rods (80-200 cm length), cuttings (20 cm) and large cuttings (40 cm). These are planted at different rates per hectare, which will depend on the individual plantation harvesting and production requirements. The planting density per hectare can vary considerably depending on factors including: the desired harvesting cycle; the final end use requirements; the rate of plantation growth required (for example poles will achieve maximum yield in a shorter timeframe when compared to a 20 cm cutting, but are often 8-10 times the price); the variety selected or needed; and the location where it is being planted.

Poplar SRC (like willow SRC) can be planted in either twin rows or a single row system. This depends on the harvesting cycle length and the end use requirement (typically cutting or rod production is planted in twin rows).

7.2 Results and conclusions

Despite our best efforts, only three sites with the potential to supply poplar SRC samples were found. Sampling locations for the poplar SRC are shown in Figure 7-1.

Figure 7-1: Sampling locations for poplar SRC



Due to having so few data points (three) for the poplar SRC analysis, it was not possible to draw any firm conclusions. Nevertheless the poplar SRC feedstock characteristics obtained in this study typically fall within the range of each equivalent poplar SRF results - this is considered briefly in Section 8.6. No detailed statistical analysis could be performed on the poplar SRC data.

8 Poplar SRF

8.1 Introduction

Broadleaved species grown in Britain are being used as a source of fuel, mainly for heat production at a moderate scale, but the biomass is rarely from purpose-grown crops; rather it is generated opportunistically from thinning operations, arboricultural activities, large-dimension branch wood remaining after the main stem has been removed for higher value markets, or felling of small numbers of trees which cannot be handled and processed profitably even for higher value markets. In some localities, there is a vibrant market for the denser wood from broadleaved species as domestic firewood often preferred to conifer wood which is generally less dense. There is however potential to use the resource at a greater scale and for a wider range of conversion technologies. Poplar was selected as a promising candidate if broadleaved species were to be grown as a bio-energy feedstock.

At present bio-energy from short rotation forestry is still a developing market and in the meantime there is no single approach to harvesting from woodland currently managed for other purposes. It is not unrealistic however to visualise a situation where different portions of the same tree are used for different markets if the overall value of the product mix justifies the additional cost of the segregation, e.g. large-dimension straight trunks for construction but branches and stems with smaller diameters and poorer form for energy. Consequently it is of interest to consider two separate fractions: the lower stem and the upper stem with the associated branches. It is very unlikely that the bark of poplar could be removed profitably; therefore the investigation considered lower stem samples with the bark attached. Normal forestry practice is to harvest broadleaved species during winter when the trees are leafless but there could well be circumstances when this is not possible or desirable, therefore the characteristics of poplar leaves have also been investigated.

The variability of poplar SRF was investigated in two different studies. Study 1 investigated the effect of the climate zone (warm/dry, warm/moist), soil type (light, medium), harvest time (April, July) and storage (no storage or three months' outside storage) on feedstock characteristics (see Figure 8-1 for the geographical location of these sites). Both plant parts - the lower stem and the upper stem with the associated branches - were analysed at both harvest times. A smaller experiment (Study 3) collected leaves only from the same sites in July. In order to minimise variability due to varietal differences, four trees of each of three varieties (Gaver, Ghoy and Gibecq) were sampled at each site in both Study 1 and 3.

Because of the sampling design, Study 1 also allowed the interactions between the structured factors to be investigated, for example the response to storage could be different in warm/dry climate zones compared to warm/moist climate zones. To investigate the importance of these factors, the original design intended that there were three sites in each combination of climate zone and soil type. A set of 11 sites was identified, of which eight were on warm/dry climate zones and three were in warm/moist zones. The original design called for three mineral soil types, i.e. light, medium and heavy, and sites were selected on the basis of GIS analysis to meet this criterion. However, analysis of the soil samples taken showed that they came from only two mineral soil types; light and medium. Each was well represented in warm/dry climate zone but soil types were not balanced within the warm/moist climate zone (see Table 8-1). Nevertheless, it was possible to complete an analysis of the impact of the four factors (climate

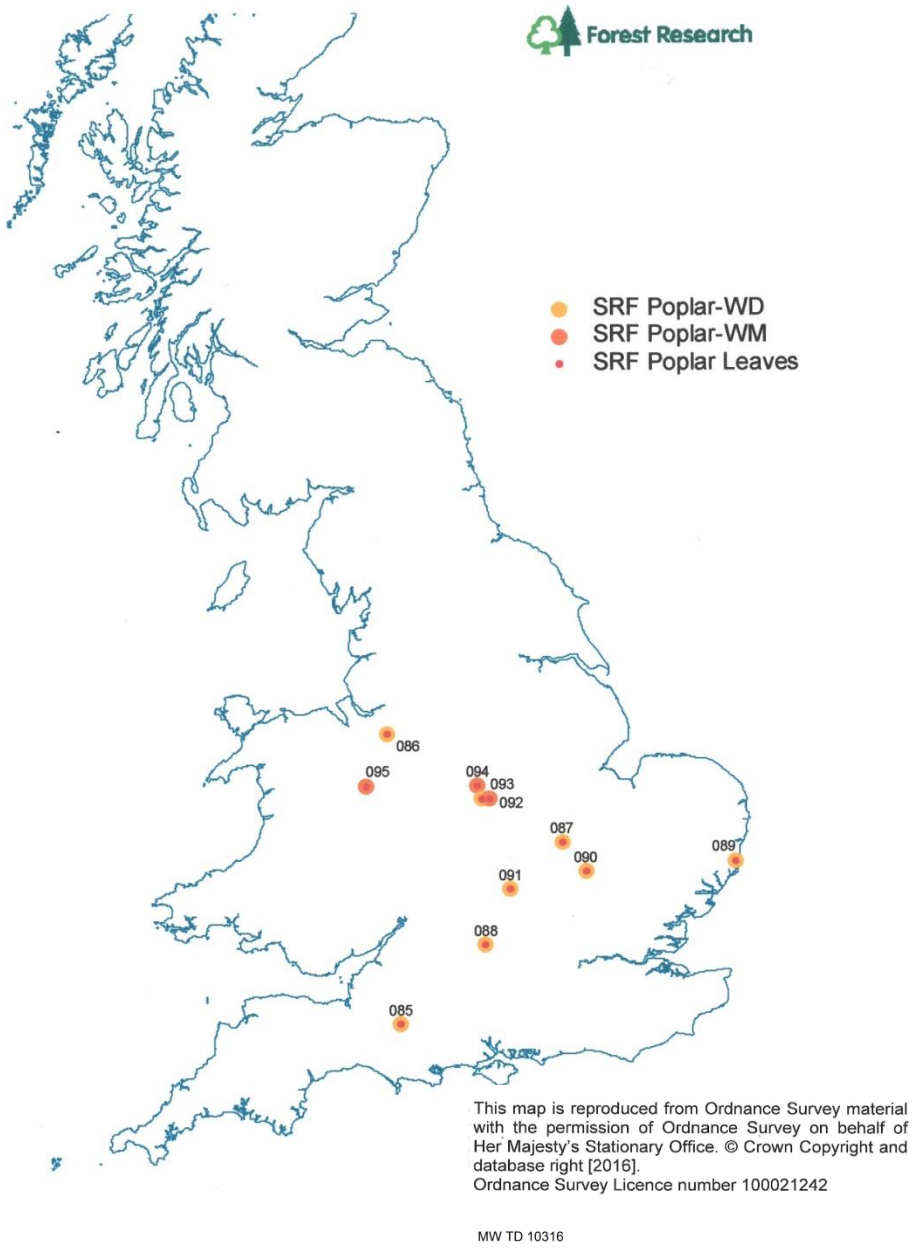
zone, soil type, harvest time and storage) on feedstock characteristics. This structured analysis is presented in Section 8.2.

Table 8-1: Distribution of samples across different soil types and climate zones

Soil type / Climate zone	Light	Medium
Warm/dry	4	4
Warm/moist	2	1

Information on many aspects of each site was collected for the purpose of understanding reasons for any observed differences in the feedstock characteristics. The provenance information included management factors as discussed in Section 3.2. Study 1 allowed the effect of these potential explanatory variables to be assessed (see Section 8.2).

Figure 8-1: Sampling locations for poplar SRF (WD = warm/dry climate; WM = warm/moist climate)



8.2 Results of structured analysis of the effect of climate zone, soil type and storage on feedstock characteristics

For poplar SRF, the structured analysis was undertaken separately on the three plant parts examined in this project – trunk, tops and leaves. The sampling matrix for the trunk and tops included climate zone, soil type, harvest time and storage, whilst that for the leaves only involved the factors climate zone and soil type. The dataset for the leaves was consequentially much smaller.

8.2.1 Trunk

Table 8-2 provides an overview of the impact of the four experimental variables climate zone (CZ), soil type (ST), harvest time (HT) and storage (STORE), and also their interactions. Storage as a main effect had a statistically significant impact on the greatest number of feedstock characteristics, followed by the harvesting time. Soil type significantly influenced only a few characteristics and climate zone affected only one. There were however several highly significant two-way interactions which were mainly between storage and harvesting time. In addition, there were a few three-way interactions, mostly involving climate zone, soil type and harvesting time.

Before exploring and describing the statistically significant effects further, each feedstock characteristic identified in the statistical analysis was reviewed according to the measured mean values in relation to the analytical limits of detection, its analytical error, and operational significance (see Section 2.6.4 for further explanation). Regardless of statistical significance, all effects that were at the limit of detection, within the analytical error, or judged to have limited operational impact were not reviewed further for this feedstock and plant part. Table 8-3 shows how each of the feedstock characteristics was assessed; those that remained following this screening step were not only statistically significant but also analytically and operationally significant and consequently warranted further examination and discussion.

Storage had an impact on moisture content of the poplar SRF trunks, although this was more apparent for the first harvest than the second harvest (April and July respectively); NCV was also strongly influenced as a consequence. Figure 8-2 illustrates the changes in moisture content for all the poplar SRF plant parts, whilst Figure 8-3 demonstrates the impact on NCV. The contrasting drying behaviour for the two harvests is clear to see.

Table 8-2: Structured factor analysis of the poplar SRF trunk data

Variable (basis)†	CZ	ST	HT	STORE	CZ & ST	CZ & HT	ST & HT	CZ & STORE	ST & STORE	HT & STORE	CZ & ST & HT	CZ & ST & STORE	CZ & HT & STORE	ST & HT & STORE	CZ & ST & HT & STORE
Moisture (ar)	0.287	0.547	0.694	0.000	0.046	0.711	0.325	0.169	0.548	0.000	0.925	0.185	0.345	0.543	0.679
Net calorific value (ar)	0.301	0.515	0.760	0.000	0.058	0.765	0.315	0.244	0.578	0.000	0.964	0.199	0.378	0.687	0.725
Ash content (d)	0.983	0.859	0.846	0.172	0.580	0.905	0.553	0.968	0.644	0.006	0.568	0.568	0.023	0.843	0.909
Volatile matter (DAF)	0.501	0.906	0.924	0.000	0.291	0.306	0.308	0.012	0.011	0.003	0.594	0.484	0.052	0.859	0.355
Gross calorific value (DAF)	0.274	0.598	0.244	0.009	0.076	0.495	0.527	0.099	0.833	0.001	0.517	0.666	0.532	0.136	0.839
Carbon (DAF)	0.219	0.219	0.192	0.382	0.100	0.181	0.187	0.282	0.881	0.000	0.117	0.702	0.752	0.669	0.268
Hydrogen (DAF)	0.988	0.859	0.014	0.493	0.547	0.680	0.494	0.084	0.719	0.002	0.616	0.920	0.421	0.954	0.888
Nitrogen (DAF)	0.419	0.467	0.000	0.000	0.259	0.025	0.337	0.000	0.622	0.000	0.010	0.500	0.541	0.483	0.079
Sulphur (DAF)	0.573	0.350	0.357	0.357	0.589	0.573	0.350	0.573	0.350	0.357	0.589	0.589	0.573	0.350	0.589
Chlorine (DAF)	0.441	0.315	0.003	0.295	0.219	0.441	0.315	0.613	0.455	0.295	0.219	0.219	0.613	0.455	0.219
Barium (d)	0.311	0.212	0.058	0.954	0.950	0.010	0.431	0.568	0.467	*	0.219	0.752	*	*	*
Chromium (d)	0.619	0.099	0.335	0.233	0.922	0.707	0.101	0.596	0.607	*	0.664	0.662	*	*	*
Cobalt (d)	0.254	0.842	0.117	0.735	0.961	0.639	0.202	0.716	0.667	*	0.841	0.518	*	*	*
Copper (d)	0.604	0.038	0.187	0.331	0.206	0.603	0.628	0.058	0.899	*	0.671	0.319	*	*	*
Molybdenum (d)	0.785	0.717	0.178	0.350	0.530	0.028	0.715	0.127	0.752	*	0.527	0.584	*	*	*
Nickel (d)	0.265	0.637	0.730	0.009	0.708	0.803	0.811	0.841	0.317	*	0.498	0.766	*	*	*
Vanadium (d)	0.588	0.789	0.533	0.011	0.238	0.000	0.143	0.281	0.544	*	0.105	0.853	*	*	*
Zinc (d)	0.950	0.948	0.690	0.592	0.628	0.073	0.854	0.206	0.926	*	0.308	0.525	*	*	*
Cadmium (d)	0.774	0.886	0.260	0.012	0.679	0.916	0.880	0.440	0.042	*	0.970	0.483	*	*	*
Lead (d)	0.268	0.636	0.270	0.164	0.066	0.232	0.264	0.150	0.479	*	0.758	0.251	*	*	*
Al_2O_3 (na)	0.547	0.044	0.877	0.002	0.999	0.423	0.395	0.344	0.204	*	0.948	0.943	*	*	*
BaO (na)	0.276	0.118	0.274	0.833	0.875	0.487	0.934	0.731	0.887	*	0.669	0.217	*	*	*
$CaCO_3$ (na)	0.959	0.352	0.045	0.438	0.457	0.141	0.510	0.081	0.523	*	0.158	0.591	*	*	*
Fe_2O_3 (na)	0.488	0.231	0.811	0.044	0.401	0.032	0.429	0.408	0.604	*	0.501	0.442	*	*	*
K_2O (na)	0.822	0.841	0.000	0.000	0.123	0.020	0.277	0.156	0.124	*	0.023	0.227	*	*	*
MgO (na)	0.068	0.406	0.576	0.741	1.000	0.824	0.560	0.734	0.670	*	0.255	0.829	*	*	*
Mn_3O_4 (na)	0.022	0.431	0.003	0.000	0.085	0.000	0.000	0.000	0.000	*	0.000	0.000	*	*	*

Variable (basis)†	CZ	ST	HT	STORE	CZ & ST	CZ & HT	ST & HT	CZ & STORE	ST & STORE	HT & STORE	CZ & ST & HT	CZ & ST & STORE	CZ & HT & STORE	ST & HT & STORE	CZ & ST & HT & STORE
Na_2O (na)	0.728	0.364	0.647	0.487	0.266	0.623	0.925	0.321	0.090	*	0.645	0.301	*	*	*
P_2O_5 (na)	0.283	0.615	0.454	0.253	0.569	0.723	0.992	0.995	0.758	*	0.291	0.649	*	*	*
SiO_2 (na)	0.829	0.188	0.850	0.001	0.755	0.549	0.339	0.388	0.491	*	0.945	0.598	*	*	*
TiO_2 (na)	0.750	0.102	0.084	0.618	0.942	0.971	0.110	0.387	0.784	*	0.729	0.584	*	*	*
Aluminium (d)	0.390	0.052	0.716	0.001	0.932	0.599	0.619	0.385	0.172	*	0.957	0.909	*	*	*
Calcium (d)	0.447	0.456	0.313	0.717	0.426	0.396	0.544	0.165	0.971	*	0.928	0.878	*	*	*
Iron (d)	0.842	0.303	0.421	0.283	0.966	0.904	0.116	0.682	0.788	*	0.598	0.702	*	*	*
Potassium (d)	0.486	0.687	0.001	0.000	0.294	0.018	0.398	0.611	0.272	*	0.064	0.253	*	*	*
Magnesium (d)	0.174	0.610	0.068	0.479	0.748	0.007	0.990	0.133	0.899	*	0.689	0.958	*	*	*
Manganese (d)	0.134	0.450	0.009	0.000	0.088	0.000	0.005	0.000	0.000	*	0.000	0.000	*	*	*
Sodium (d)	0.847	0.300	0.369	0.537	0.445	0.115	0.445	0.295	0.133	*	0.712	0.315	*	*	*
Phosphorous (d)	0.196	0.816	0.538	0.091	0.493	0.041	0.995	0.463	0.795	*	0.740	0.469	*	*	*
Silicon (d)	0.741	0.224	0.771	0.001	0.707	0.603	0.496	0.385	0.506	*	0.962	0.597	*	*	*
Titanium (d)	0.765	0.031	0.029	0.659	0.662	0.517	0.035	0.462	0.835	*	0.375	0.628	*	*	*
Alkali index	0.483	0.744	0.001	0.000	0.298	0.014	0.451	0.642	0.222	*	0.061	0.232	*	*	*

†basis of analysis; ar = as received fuel, d = dry fuel, DAF = dry, ash-free fuel, na= normalised ash. Antimony, arsenic, mercury and bromine were not included in the structured analysis due to limits of detection. Dark blue cells indicate $p<0.001$; light blue cells $0.001<p<0.05$

Table 8-3: Mean values and assessment of relevance for main effects and interactions identified by structured analysis for poplar SRF trunk (number of analyses if not default)

One factor analysis			
Variable	Storage		Assessment
	Fresh	Stored	
Default number of analyses	22	11	
Ni, mg/kg (d)	0.30	0.23	Unlikely to have operational impact
V, mg/kg (d)	0.12	0.08	Limit of detection level
Al_2O_3, %wt (na)	0.89	0.45	Relevant for further study
Fe_2O_3, %wt (na)	0.35 (21)	0.23	Relevant for further study
K_2O, %wt (na)	15.34	19.98	Relevant for further study
SiO_2, %wt (na)	2.84	0.64	Relevant for further study
Al, mg/kg (d)	62.7	33.4	Relevant for further study
K, mg/kg (d)	1747	2360	Relevant for further study
Si, mg/kg (d)	176.3	41.8	Relevant for further study
Alkali Index	0.111	0.149	Relevant for further study
Mn_3O_4, %wt (na)	0.10 (21)	0.08	Unlikely to have operational impact
	Soil type		
	Light	Medium	
Default number of analyses	18	15	
Cu, mg/kg (d)	3.01	2.24	Unlikely to have operational impact
Al_2O_3, %wt (na)	0.92	0.52	Relevant for further study
	Harvest time		
	1	2	
Default number of analyses	22	22	
Chlorine, %wt (DAF)	0.01	0.01	Limit of detection level
$CaCO_3$, wt% (na)	67.25	69.32 (11)	Unlikely to have operational impact

Two factor analysis				
Variable	Climate Zone / Harvest time	Warm/dry	Warm/moist	Assessment
Default number of analyses	1	16	6	
	2	8	3	
N, %wt (DAF)	1	0.31	0.29 (6)	Relevant for further study
	2	0.28	0.28 (6)	
Ba, mg/kg (d)	1	5.40 (15)	7.99	Unlikely to have operational impact
	2	5.56	10.79	
Mo, mg/kg (d)	1	0.09	0.08	Exclude – at or below limit of detection level
	2	0.09	0.1	
V, mg/kg (d)	1	0.12	0.08	Exclude – at or below limit of detection level
	2	0.09(7)	0.18	
Fe_2O_3, %wt (na)	1	0.33	0.28	Relevant for further study
	2	0.18 (7)	0.53	

	Climate Zone / Harvest time	Warm/dry	Warm/moist	Assessment
K, mg/kg (d)	1	2093	2090	Relevant for further study
	2	1848	1189	
Mg, mg/kg (d)	1	416.5	547.3	Unlikely to have operational impact
	2	414.1	466.1	
P, mg/kg (d)	1	368.3	319.5	Exclude – within repeatability of analysis
	2	376.5	268.5	
Alkali Index	1	0.133	0.133	Relevant for further study
	2	0.119	0.076	
K_2O, %wt (na)	1	17.66	18.55	Relevant for further study
	2	15.77	12.47	
	Climate Zone / Soil Type	Warm/dry	Warm/moist	Assessment
Moisture % wt (ar)	Light	53.69 (16)	56.18 (8)	Relevant for further study
	Medium	54.2 (16)	52.58 (4)	
	Climate Zone / Storage	Warm/dry	Warm/moist	Assessment
Default number of analyses	0	16	6	
Volatile matter, %wt (DAF)	Fresh	84.3	84.7	Unlikely to have operational impact
	Stored	83.8	83.7	
N, %wt (DAF)	Fresh	0.30	0.32	Relevant for further study
	Stored	0.29	0.25	
	Harvest Time / Storage	1	2	Assessment
Default number of analyses		11	11	
Moisture, %wt (ar)	Fresh	58.2	54.7	Relevant for further study
	Stored	50.0	53.9	
NCV, kJ/kg (ar)	Fresh	6193	6894	Relevant for further study
	Stored	7878	7120	
Ash, %wt (d)	Fresh	1.6	1.5	Exclude – within repeatability of analysis
	Stored	1.5	1.7	
Volatile matter, %wt (DAF)	Fresh	84.2	84.5	Exclude – within repeatability of analysis
	Stored	83.9	83.6	
GCV, kJ/kg (DAF)	Fresh	19847	19787	Exclude – within repeatability of analysis
	Stored	19827	19950	
C, %wt (DAF)	Fresh	49.96	50.33	Exclude – within repeatability of analysis
	Stored	50.18	49.99	
H, %wt (DAF)	Fresh	6.13	6.12	Exclude – within repeatability of analysis
	Stored	6.10	6.17	

	Harvest Time / Storage	1	2	Assessment
N, %wt (DAF)	Fresh	0.2955	0.3164	Relevant for further study
	Stored	0.3155	0.2445	
	Soil Type / Storage	Light	Medium	Assessment
Default number of analyses		12	10	
Volatile matter, %wt (DAF)	Fresh	84.5	84.2	Unlikely to have operational impact
	Stored	83.7	83.9	
Cd, mg/kg (d)	Fresh	0.460	0.388 (8)	Relevant for further study
	Stored	0.469 (6)	0.625 (5)	
	Soil Type / Harvest time	Light	Medium	Assessment
Ti, mg/kg (d)	1	3.7 (12)	2.27 (10)	Unlikely to have operational impact
	2	12.48 (6)	2.29 (5)	

Three Factor analysis

Variable	Climate zone	Warm/dry		Warm/moist		Assessment
	Soil Type / Storage	Light	Medium	Light	Medium	
Default number of analyses	Fresh	8	8	4	2	
	Stored	4	4	2	1	
Mn_3O_4, %wt (na)	Fresh	0.07 (7)	0.07	0.11	0.26	Unlikely to have operational impact
	Stored	0.08	0.08	0.10	0.04	
Mn, mg/kg (d)	Fresh	8.14	7.51	9.54	27.25	Unlikely to have operational impact
	Stored	9.07	8.44	8.82	4.32	
	Soil Type / Harvest time	Light	Medium	Light	Medium	
Default number of analyses	1	8	8	4	2	
	2	4	4	2	1	
N, %wt (DAF)	1	0.30	0.32	0.30	0.26	Relevant for further study
	2	0.27 (8)	0.29 (8)	0.28 (4)	0.30 (2)	
K_2O, %wt (na)	1	16.48	18.84	21.14	13.35	Relevant for further study
	2	14.77	16.76	12.34	12.72	
Mn_3O_4, %wt (na)	1	0.08	0.07	0.10	0.26	Unlikely to have operational impact
	2	0.07 (3)	0.08	0.12	0.04	
Mn, mg/kg (d)	1	8.59	7.66	9.59	27.25	Unlikely to have operational impact
	2	8.19	8.14	8.71	4.32	

Figure 8-2: Results from the moisture (ar) analysis of poplar SRF in study 1, showing harvest time impacts in study 1 & 3

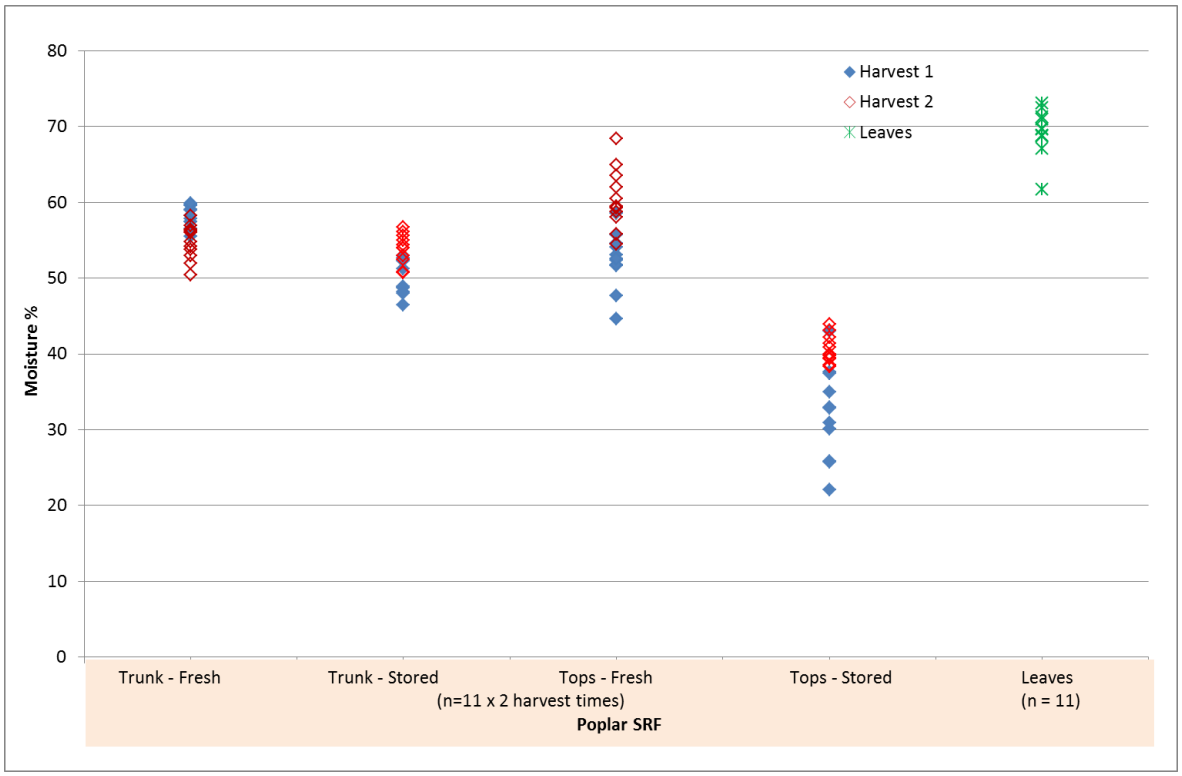
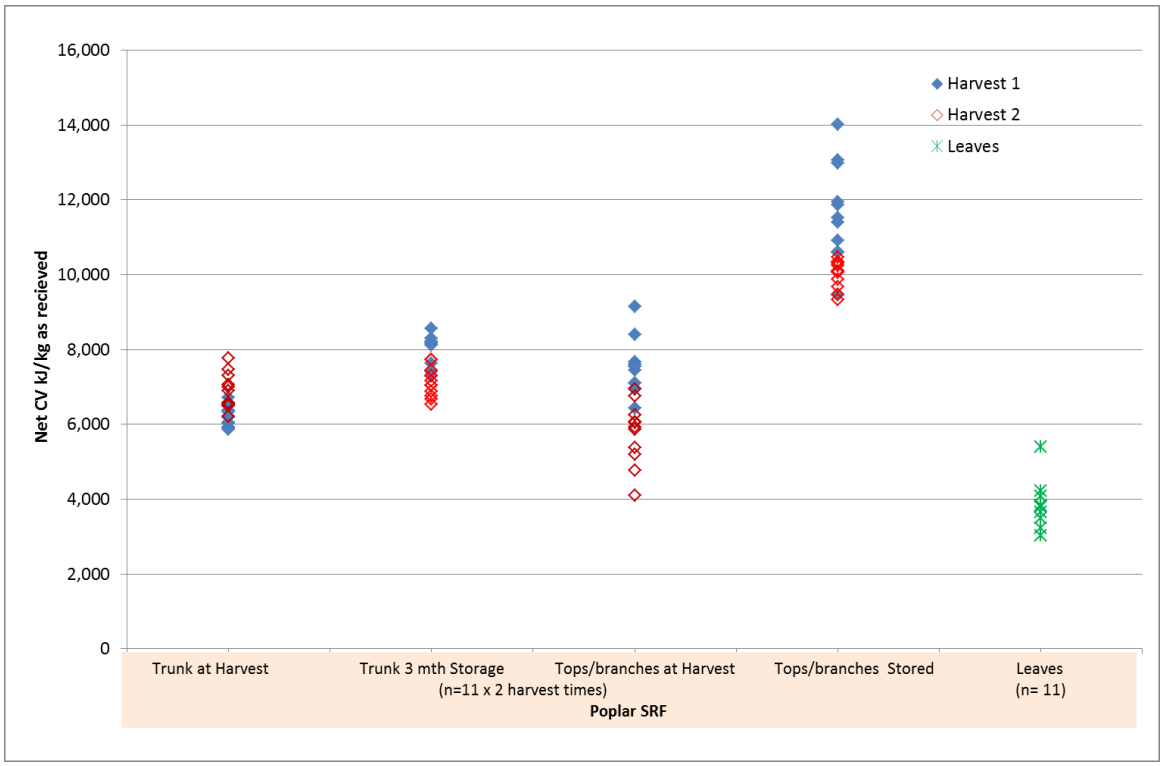
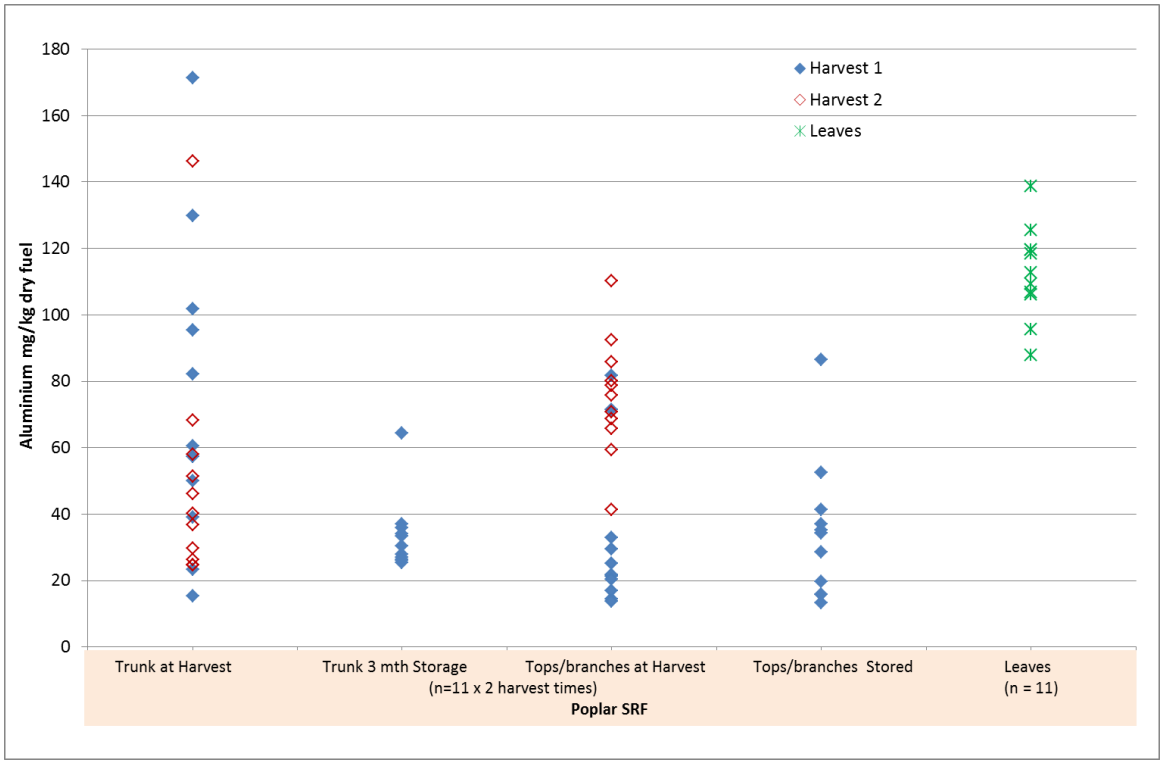


Figure 8-3: Results from the NCV (ar) analysis of poplar SRF in study 1, showing harvest time impacts in study 1 & 3



Storage also appeared to affect to some extent the levels of a number of macroelements in the poplar SRF trunks, including aluminium, potassium and silicon (and their respective oxides in ash), the concentrations generally decreasing on storage with the exception of potassium which increased. The behaviour of aluminium is shown in Figure 8-4 below. Note that only the stored material from the first harvest was analysed for trace and macroelements.

Figure 8-4: Results from the aluminium (d) analysis of poplar SRF in study 1, showing harvest time impacts in study 1 & 3 (note: back-calculated from aluminium oxide in ash)



It is judged that the other statistically significant storage impacts can be disregarded as the changes were either operationally insignificant or at the limit of detection of the analysis, as shown in Table 8-3.

Although a number of impacts were highlighted for harvest time, closer inspection suggests that the majority of the changes can be disregarded, although the data for dry nitrogen tended to increase slightly from the first to the second harvest.

The statistics suggested manganese was the only characteristic impacted by climate zone; it is clear from Table 8-3 that manganese is also impacted by many of the two and three-variable combinations of structured factors. However, the resulting changes in manganese concentration were always judged to be operationally insignificant.

Soil type also had very limited impact on the poplar SRF trunk characteristics, despite the expectation that there might be a close relationship between elements in the soil and the feedstock. The only impact judged to be worthy of comment was that for Al_2O_3 in the ash, which did appear to be lower in the medium soil type compared to the light soil type, the differences for all other characteristics being operationally insignificant.

The six possible two-way interactions between the four structured factors had a large number of statistically significant impacts, particularly for the combinations of climate zone & harvest time and harvest time & storage. There appeared to be some effect of climate zone & soil type on moisture content, although sample numbers for the warm/moist climate zone are low.

The combination of climate zone & harvest time was significant for some feedstock characteristics (dry nitrogen, Fe_2O_3 in ash and potassium in fuel), but most can be disregarded as the data are either at the limit of detection, operationally insignificant or closer than the analytical repeatability; once again the sample numbers for the warm/moist soil condition are low (three samples). The few impacts caused by the combination of soil type & harvest time are all judged to be operationally insignificant, as are those for the combinations of climate zone & storage (with the possible exception of dry nitrogen) and soil type & storage. Finally, as shown in Figure 8-2 and Figure 8-3, the combination of harvest time and storage has a strong influence on moisture and NCV, particularly for the first harvest – all other impacts for this particular combination were within analytical repeatability. The four 'three-way' interactions of the four structured factors show few impacts and the majority of the differences are judged to be operationally insignificant, with the exception of dry nitrogen and K_2O in ash. The final 'four-way' interaction between all four factors indicated no impacts worthy of more detailed interpretation.

8.2.2 Tops (including branches)

Of the four structured factors investigated, harvesting time as a main effect had a significant impact on the greatest number of feedstock characteristics of the tops with many effects being very highly significant i.e. $p<0.001$ (see Table 8-4). The next most influential factor was storage, with relatively few feedstock properties influenced by climate zone and soil type. Fewer impacts were observed from combinations of two factors, whilst the combinations of three and four factors affected just a handful of characteristics.

Harvest time had the biggest impact of all the factors although many of the changes were judged to be operationally insignificant or the measurements were at the limit of detection (see Table 8-5 and Table 8-6). The following effects are all notable; compared to the first harvest (April), samples collected at the second harvest (July) increased in moisture and consequently decreased in NCV (see Figure 8-2 and Figure 8-3); likewise the ash content of the fresh material from the second harvest was 2% higher than the first harvest – see Figure 8-5. This is likely to be a result of the presence of leaf material on the tops during the second harvest, as the ash and moisture levels in leaves are high (see Section 8.2.3).

Figure 8-5: Results from the ash (d) analysis of poplar SRF & poplar SRC in study 1, showing harvest time impacts and leaf analysis from study 3

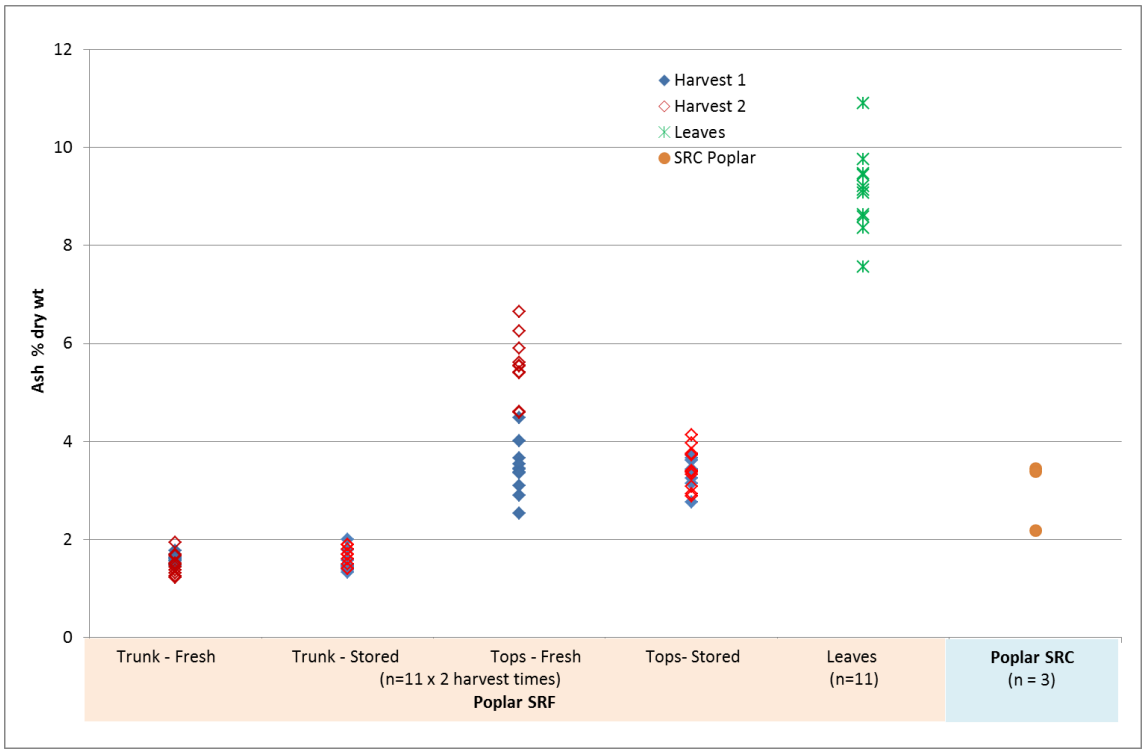


Table 8-4: Structured factor analysis of poplar SRF Tops

Variable	CZ	ST	HT	STORE	CZ & ST	CZ & HT	ST & HT	CZ & STORE	ST & STORE	HT & STORE	CZ & ST & HT	CZ & ST& STORE	CZ & HT & STORE	St & HT & STORE	CZ & ST & HT & STORE
Moisture (ar)	0.407	0.451	0.000	0.000	0.303	0.049	0.512	0.865	0.617	0.871	0.435	0.378	0.652	0.558	0.547
Net calorific value (ar)	0.321	0.515	0.000	0.000	0.356	0.040	0.601	0.768	0.565	0.832	0.407	0.389	0.613	0.543	0.581
Ash content (d)	0.861	0.792	0.000	0.000	0.649	0.158	0.719	0.315	0.964	0.000	1.000	0.391	0.370	0.280	1.000
Volatile matter (DAF)	0.123	0.469	0.000	0.012	0.665	0.469	0.484	0.705	0.815	0.000	0.028	0.641	0.130	0.091	0.739
Gross calorific value (DAF)	0.305	0.743	0.001	0.000	0.552	0.867	0.133	0.607	0.546	0.883	0.535	0.866	0.498	0.428	0.478
Carbon (DAF)	0.056	0.906	0.000	0.002	0.802	0.521	0.670	0.163	0.259	0.000	0.598	0.268	0.271	0.666	0.598
Hydrogen (DAF)	0.871	0.687	0.144	0.000	0.201	0.456	0.955	0.578	0.469	0.436	0.945	0.938	0.994	0.921	0.151
Nitrogen (DAF)	0.899	0.446	0.000	0.000	0.225	0.128	0.324	0.630	0.391	0.000	0.561	0.423	0.977	0.465	0.626
Sulphur (DAF)	0.599	0.190	0.000	0.000	0.154	0.135	0.044	0.208	0.159	0.000	0.190	0.505	0.424	0.304	0.185
Chlorine (DAF)	0.039	0.381	0.000	0.000	0.192	0.361	0.482	0.090	0.230	0.000	0.005	0.915	0.897	0.721	0.000
Barium (d)	0.313	0.214	0.182	0.581	0.804	0.113	0.782	0.523	0.399	*	0.624	0.535	*	*	*
Chromium (d)	0.536	0.806	0.073	0.775	0.955	0.720	0.493	0.482	0.288	*	0.605	0.686	*	*	*
Cobalt (d)	0.350	0.736	0.000	0.678	0.642	0.086	0.516	0.973	0.940	*	0.269	0.857	*	*	*
Copper (d)	0.505	0.519	0.001	0.282	0.710	0.383	0.195	0.983	0.821	*	0.764	0.504	*	*	*
Molybdenum (d)	0.985	0.784	0.000	0.113	0.661	0.055	0.757	0.936	1.000	*	0.858	0.535	*	*	*
Nickel (d)	0.472	0.990	0.000	0.156	0.741	0.690	0.121	0.433	0.752	*	0.439	0.929	*	*	*
Vanadium (d)	0.560	0.834	0.000	0.051	0.205	0.003	0.633	0.333	0.263	*	0.457	0.793	*	*	*
Zinc (d)	0.778	0.551	0.000	0.675	0.983	0.279	0.720	0.907	0.726	*	0.425	0.567	*	*	*
Cadmium (d)	0.719	0.867	0.543	0.189	0.747	0.749	0.816	0.378	0.454	*	0.935	0.209	*	*	*
Lead (d)	0.973	0.175	0.775	0.728	0.942	0.480	0.758	0.770	0.789	*	0.971	0.937	*	*	*
Al_2O_3 (na)	0.000	0.697	0.000	0.430	0.000	0.093	0.253	0.799	0.807	*	0.025	0.729	*	*	*
BaO (na)	0.246	0.178	0.055	0.121	0.886	0.404	0.729	0.652	0.294	*	1.000	0.795	*	*	*
$CaCO_3$ (na)	0.673	0.530	0.000	0.799	0.538	0.286	0.350	0.916	0.529	*	0.516	0.801	*	*	*
Fe_2O_3 (na)	0.083	0.490	0.032	0.101	0.028	0.098	0.807	0.603	0.919	*	0.099	0.255	*	*	*
K_2O (na)	0.959	0.393	0.000	0.475	0.383	0.415	0.591	0.788	0.643	*	0.581	0.568	*	*	*
MgO (na)	0.422	0.616	0.211	0.648	0.802	0.151	0.378	0.630	0.999	*	0.895	0.819	*	*	*
Mn_3O_4 (na)	0.946	0.632	0.016	0.261	0.306	0.709	0.156	0.819	0.511	*	0.120	0.952	*	*	*

Variable	CZ	ST	HT	STORE	CZ & ST	CZ & HT	ST & HT	CZ & STORE	ST & STORE	HT & STORE	CZ & ST & HT	CZ & ST& STORE	CZ & HT & STORE	St & HT & STORE	CZ & ST & HT & STORE
Na_2O (na)	0.034	0.009	0.000	0.001	0.299	0.387	0.653	0.878	0.890	*	0.994	0.910	*	*	*
P_2O_5 (na)	0.569	0.901	0.001	0.258	0.389	0.318	0.361	0.287	0.923	*	0.830	0.560	*	*	*
SiO_2 (na)	0.592	0.906	0.000	0.996	0.299	0.159	0.366	0.887	0.957	*	0.898	0.680	*	*	*
TiO_2 (na)	0.538	0.438	0.268	0.460	0.621	0.149	0.286	0.265	0.516	*	0.960	0.544	*	*	*
Aluminium (d)	0.001	0.643	0.000	0.641	0.000	0.915	0.571	0.718	0.570	*	0.365	0.663	*	*	*
Calcium (d)	0.996	0.626	0.000	0.872	0.378	0.050	0.683	0.771	0.383	*	0.376	0.449	*	*	*
Iron (d)	0.058	0.490	0.610	0.243	0.005	0.635	0.958	0.615	0.582	*	0.447	0.301	*	*	*
Potassium (d)	0.804	0.855	0.000	0.472	0.900	0.792	0.480	0.833	0.459	*	0.359	0.924	*	*	*
Magnesium (d)	0.278	0.689	0.000	0.938	0.889	0.029	0.686	0.854	0.689	*	0.442	0.723	*	*	*
Manganese (d)	0.978	0.560	0.000	0.200	0.391	0.165	0.457	0.766	0.791	*	0.208	0.804	*	*	*
Sodium (d)	0.036	0.011	0.019	0.023	0.438	0.330	0.558	0.773	0.579	*	0.691	0.667	*	*	*
Phosphorous (d)	0.578	0.779	0.000	0.692	0.566	0.039	0.463	0.601	0.436	*	0.795	0.350	*	*	*
Silicon (d)	0.430	0.786	0.000	0.977	0.060	0.588	0.268	0.854	0.821	*	0.162	0.646	*	*	*
Titanium (d)	0.464	0.558	0.003	0.561	0.479	0.081	0.263	0.288	0.560	*	0.983	0.539	*	*	*
Alkali index	0.746	0.777	0.000	0.461	0.897	0.739	0.532	0.849	0.449	*	0.339	0.938	*	*	*

†basis of analysis; ar = as received fuel, d = dry fuel, DAF = dry, ash-free fuel, na= normalised ash. Antimony, arsenic, mercury and bromine were not included in the structured analysis due to limits of detection. Dark blue cells indicate $p<0.001$; light blue cells $0.001<p<0.05$

Table 8-5: Mean values and assessment of relevance for main effects and interactions identified by structured analysis for poplar SRF tops (number of analyses if not default)

One factor analysis			
	Storage		
Variable	Fresh	Stored	Assessment
Default number of analyses	22	22	
Moisture, %wt (ar)	56.45	36.4	Relevant for further study
NCV, kJ/kg (ar)	6648	10832	Relevant for further study
GVC, KJ/kg (DAF)	20642	20424	Exclude – within repeatability of analysis
H, %wt (DAF)	6.24	6.13	Exclude – within repeatability of analysis
Na_2O, %wt (na)	0.60	0.65 (11)	Unlikely to have operational impact
Na, mg/kg (d)	162.3	153.1 (11)	Unlikely to have operational impact
	Soil type		
	Light	Medium	
Default number of analyses	18	15	
Chlorine, %wt (DAF)	0.02 (24)	0.02 (20)	Exclude – within repeatability of analysis
Na_2O, %wt (na)	0.72	0.49	Relevant for further study
Na, mg/kg (d)	186.1	127	Relevant for further study
	Harvest Time		
	1	2	
Default number of analyses	22	11	
Moisture, %wt (ar)	42.3	50.6 (22)	Relevant for further study
NCV, kJ/kg (ar)	9605	7875 (22)	Relevant for further study
GVC, KJ/kg (DAF)	20455	20610 (22)	Exclude – within repeatability of analysis
Co, mg/kg (d)	0.2 (21)	0.51	Exclude – at or below limit of detection level
Cu, mg/kg (d)	6.23	8.10	Unlikely to have operational impact
Mo, mg/kg (d)	0.17	0.28	Exclude – at or below limit of detection level
Ni, mg/kg (d)	1.08	1.91	Unlikely to have operational impact
Zn, mg/kg (d)	66.85	95.93	Relevant for further study
$CaCO_3$, %wt (na)	69.13	63.32	Unlikely to have operational impact
Fe_2O_3, %wt (na)	0.17	0.13	Unlikely to have operational impact
K_2O, %wt (na)	14.55	18.56	Relevant for further study
Mn_3O_4, %wt (na)	0.09	0.11	Unlikely to have operational impact
Na_2O, %wt (na)	0.72	0.41	Unlikely to have operational impact
P_2O_5, %wt (na)	8.29	7.39	Unlikely to have operational impact
SiO_2, %wt (na)	1.18	4.42	Relevant for further study
Al, mg/kg (d)	33.15	75.37	Unlikely to have operational impact
Ca, mg/kg (d)	8849	11817	Unlikely to have operational impact
K, mg/kg (d)	3831	7226	Relevant for further study

	Harvest Time (cont.)		
	1	2	
Mn, mg/kg (d)	21.51	35.62	Unlikely to have operational impact
Na, mg/kg (d)	168.2	141.4	Unlikely to have operational impact
P, mg/kg (d)	1156	1486	Unlikely to have operational impact
Si, mg/kg (d)	177	948.1	Relevant for further study
Ti, mg/kg (d)	2.99	6.18	Unlikely to have operational impact
Alkali Index	0.245	0.455	Relevant for further study
	Climate Zone		
	Warm/dry	Warm/moist	
Default number of analyses	24	9	
Na_2O, %wt (na)	0.56	0.76	Unlikely to have operational impact
Al, mg/kg (d)	41.11	63.54	Unlikely to have operational impact
Na, mg/kg (d)	145.9	194.9	Unlikely to have operational impact

Two factor analysis				
Variable	Climate Zone / Harvest time	Warm/dry	Warm/moist	Assessment
Default number of analyses		16	6	
Moisture, %wt (ar)	1	43.4	39.3	Relevant for further study
	2	50.1	51.8	
NCV, kJ/kg (ar)	1	9351	10285	Relevant for further study
	2	7963	7640	
V, mg/kg (d)	1	0.17 (15)	0.21	Unlikely to have operational impact
	2	0.29 (8)	0.26 (3)	
Mg, mg/kg (d)	1	1025	1142	Unlikely to have operational impact
	2	1292 (8)	1904 (3)	
P, mg/kg (d)	1	1201	1035	Unlikely to have operational impact
	2	1450 (8)	1582 (3)	
	Climate Zone / Soil type	Warm/dry	Warm/moist	
Default number of analyses	Light	12	6	
	Medium	12	3	
Fe_2O_3, %wt (na)	Light	0.15	0.15	Relevant for further study
	Medium	0.14	0.27	
Al, mg/kg (d)	Light	46.6	48.9	Relevant for further study
	Medium	35.6	92.8	
Fe, mg/kg (d)	Light	38.6	37.2	Relevant for further study
	Medium	33.1	69.7	

	Soil type / Harvest time	Light	Medium	
Default number of analyses		12	10	
Sulphur, %wt (DAF)	1	0.02	0.02	
	2	0.07	0.09	Relevant for further study
	Harvest Time / Storage	1	2	
Default number of analyses		11	11	
Ash, %wt (d)	Fresh	3.4	5.5	Relevant for further study
	Stored	3.4	3.5	
Volatile matter, %wt (DAF)	Fresh	81.3	80.4	Unlikely to have operational impact
	Stored	81.1	81.2 (10)	
C, %wt (DAF)	Fresh	51.06	52.17	Unlikely to have operational impact
	Stored	51.81	52.08	
N, %wt (DAF)	Fresh	0.87 (10)	1.32	Relevant for further study
	Stored	0.78	0.82	
Sulphur, %wt (DAF)	Fresh	0.018	0.128	Relevant for further study
	Stored	0.038	0.048	
Chlorine, %wt (DAF)	Fresh	0.028	0.04	Relevant for further study
	Stored	0.02	0.02	

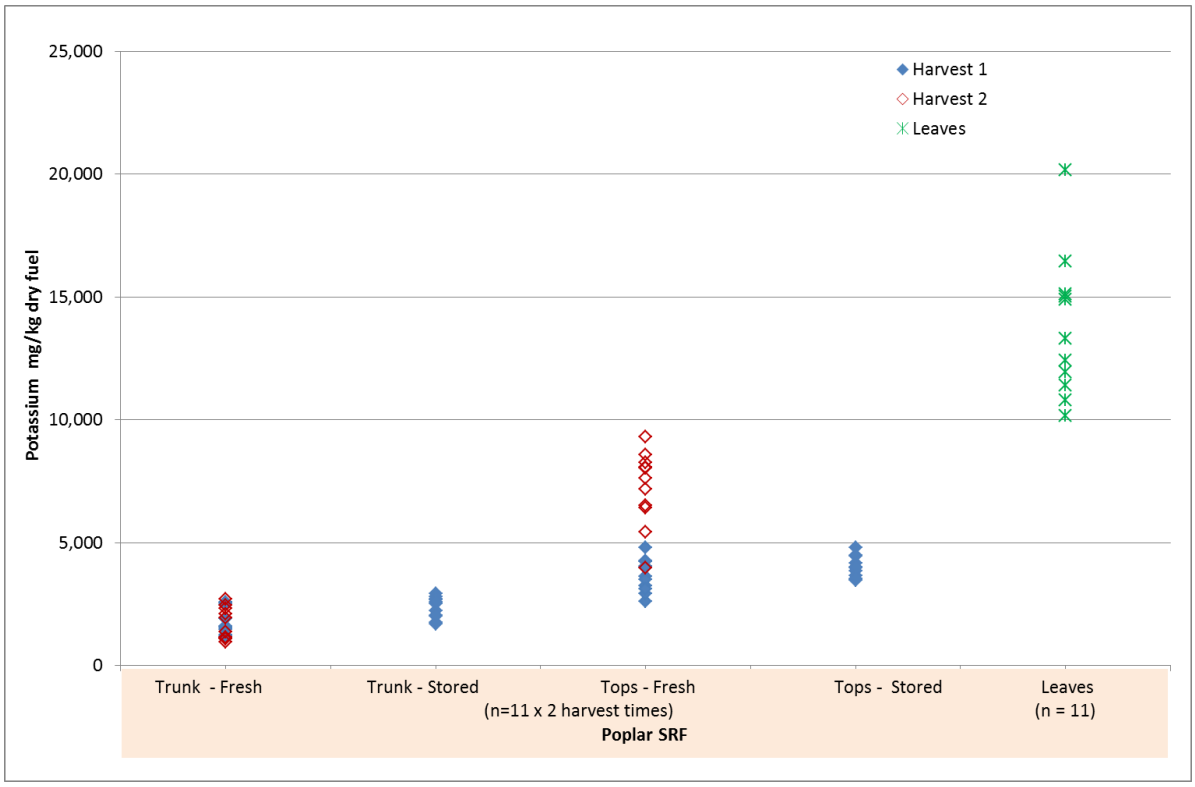
Table 8-6: Mean values and assessment of relevance for main effects and interactions identified by structured analysis for poplar SRF tops cont. (number of analyses if not default)

Three factor analysis						
Variable	Climate zone	Warm/dry		Warm/moist		Assessment
	Soil type / Harvest time	L	M	L	M	
Default number of samples		8	8	4	2	
Volatile matter, %wt (DAF)	1	81.3	81.3	81.0	80.7	Unlikely to have operational impact
	2	81.0	80.6 (7)	80.5	80.9	
Al_2O_3, %wt (na)	1	0.1825	0.1275	0.205	0.49	Unlikely to have operational impact
	2	0.3125 (4)	0.265 (4)	0.33 (2)	0.37 (1)	

Four factor analysis									
Variable	Climate zone	Warm/dry				Warm/moist			Assessment
	Soil type	Light		Medium		Light		Medium	
	Harvest Time / Storage	1	2	1	2	1	2	1	2	
Chlorine, %wt (DAF)	Fresh	0.02 (4)	0.03 (4)	0.02 (4)	0.04 (4)	0.02 (2)	0.05 (2)	0.04 (1)	0.03 (1)	Unlikely to have operational impact
	Stored	0.02 (4)	0.02 (4)	0.02 (4)	0.02 (4)	0.02 (2)	0.02 (2)	0.01 (1)	0.02 (1)	

The higher ash content of the second harvest was reflected in increased concentrations of many elements, including K_2O and SiO_2 in ash and K and Si in fuel. Figure 8-6 illustrates the behaviour of potassium in the tops, with a clear difference between harvests.

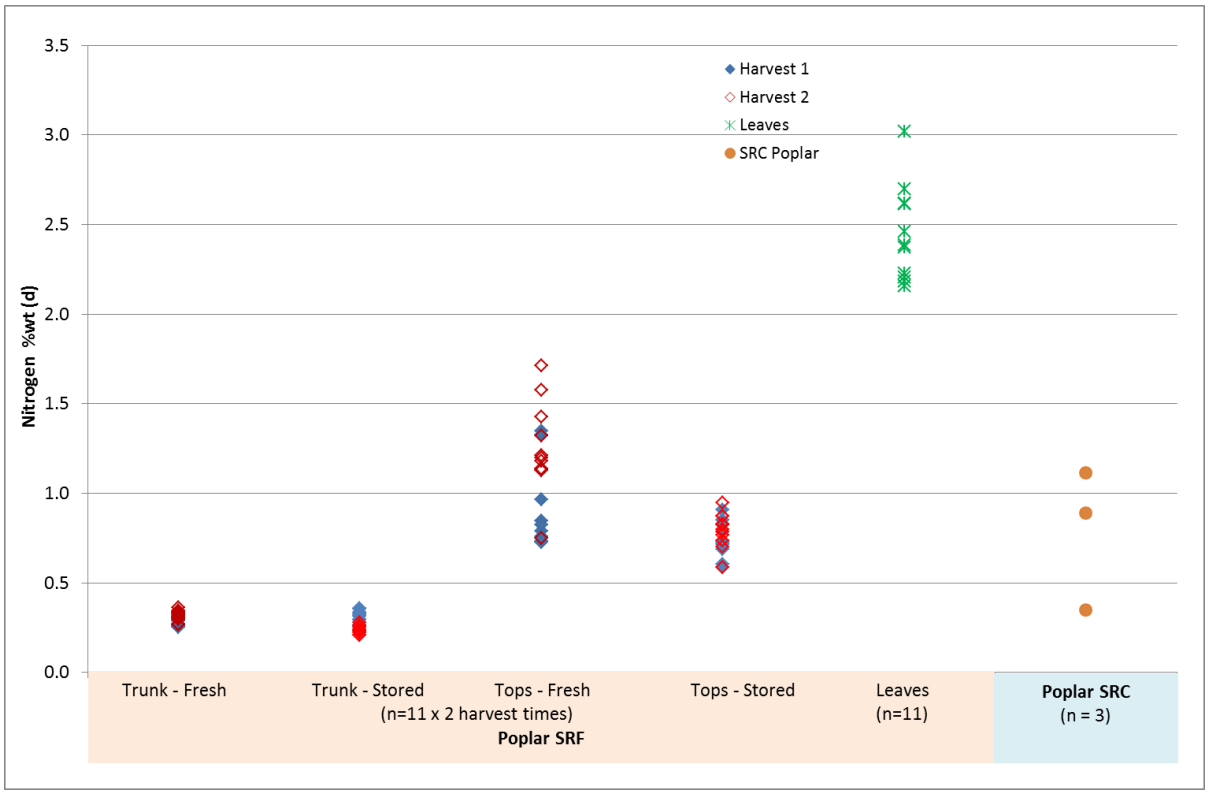
Figure 8-6: Results from the potassium (d) analysis of poplar SRF in study 1, showing harvest time impacts and leaf analysis from study 3 (note: back-calculated from potassium oxide in ash)



Significantly higher concentrations of dry nitrogen, sulphur and chlorine were also apparent in the fresh material from the second harvest. Figure 8-7 demonstrates the behaviour of dry nitrogen.

As might be expected, storage also had a large impact on the moisture content and NCV of the tops from both harvests (see Figure 8-2 and Figure 8-3), but it was interesting to note that the combination of storage & harvest time highlighted some differences in behaviour between the second and first harvests. The higher concentrations of dry ash, sulphur, chlorine and nitrogen from the second harvest all appear to reduce significantly on storage, so that the stored samples from both harvests 1 and 2 are broadly similar in composition – this is demonstrated in Figure 8-5 and Figure 8-7 above. The higher levels of these elements in the fresh second harvest material are likely to be due to the presence of leaves; during storage these may have been lost and so the stored material from the second harvest would more closely resemble that from the first harvest. Climate zone and soil type individually had few impacts on the characteristics and all were judged to be operationally insignificant.

Figure 8-7: Results from the nitrogen (d) analysis of poplar SRF & poplar SRC in study 1, showing harvest time impacts and leaf analysis from study 3



The impact of the combination of climate zone & soil type on Fe_2O_3 in ash and Fe and Al in the fuel was noted, but the low number of data points for the warm/moist climate zone and medium soil type needs to be taken into account. The combination of climate zone & harvest time affected both moisture and NCV with the second harvest being wetter, particularly for the warm/moist climate zone, the remaining impacts were operationally insignificant. The combination of soil type & harvest time also has a clear impact on sulphur concentration with the second harvest material in medium soils being higher.

The combinations of climate zone & storage and soil type & storage had no influence on any feedstock characteristic.

The four 'three-way' interactions of the structured factors show few impacts and all were judged to be operationally insignificant. The final 'four-way' interaction between all factors suggested a possible impact on chlorine, with the fresh material from the second harvest apparently higher in chlorine, with a decrease after storage, but the number of samples for each condition is very low.

8.2.3 Leaves

It was only possible to investigate the impact of climate zone and soil type on leaf characteristics since they were collected on only one occasion (July) and were not stored (Table 8-7). The statistics suggest a number of characteristics were affected by climate zone, with fewer influenced by soil type, whilst the combination of both factors impacted on three characteristics. Closer inspection of the data suggests that for climate zone, only the impacts on sodium are worthy of note as the changes for the other characteristics were operationally insignificant. The decrease in sodium content (both as the proportion of the oxide in ash and also the concentration of sodium in the fuel) as a result of moving from light to medium soil type could be significant. The combination of climate zone & soil type did show an impact on

dry ash content, with a reduction of almost 1% on moving from light to medium soils in the warm/dry scenario. There is insufficient data for the warm/moist condition to make a proper assessment. The impacts on antimony and arsenic can be disregarded, as virtually all the data were at the limit of detection, as discussed in Table 8-8.

Table 8-7: Structured factor analysis of poplar leaves

Variable	Climate Zone	Soil Type	Climate zone & Soil Type
Moisture (ar)	0.862	0.097	0.422
Net calorific value (ar)	0.854	0.069	0.230
Ash content (d)	0.644	0.412	0.039
Volatile matter (DAF)	0.510	0.876	0.431
Gross calorific value (DAF)	0.845	0.923	0.239
Carbon (DAF)	0.659	0.921	0.578
Hydrogen (DAF)	0.922	0.691	0.481
Nitrogen (DAF)	0.167	0.426	0.328
Sulphur (DAF)	0.724	0.366	0.782
Chlorine (DAF)	0.417	0.089	0.361
Barium (d)	0.063	0.150	0.899
Chromium (d)	0.297	0.217	0.150
Cobalt (d)	0.514	0.823	0.450
Copper (d)	0.936	0.311	0.682
Molybdenum (d)	0.319	0.540	0.060
Nickel (d)	0.733	0.633	0.932
Vanadium (d)	0.319	0.540	0.060
Zinc (d)	0.626	0.656	0.943
Antimony (d)	0.165	0.818	0.046
Arsenic (d)	0.165	0.818	0.046
Mercury (d)	0.424	0.262	0.596
Bromine (d)	0.441	0.855	0.336
Cadmium (d)	0.737	0.733	0.786
Lead (d)	0.295	0.163	0.736
Al_2O_3 (na)	0.113	0.494	0.152
BaO (na)	0.022	0.206	0.661
$CaCO_3$ (na)	0.791	0.480	0.673
Fe_2O_3 (na)	0.731	0.833	0.131
K_2O (na)	0.169	0.808	0.696
MgO (na)	0.208	0.713	0.818
Mn_3O_4 (na)	0.725	0.771	0.161
Na_2O (na)	0.022	0.025	0.065
P_2O_5 (na)	0.964	0.716	0.757
SiO_2 (na)	0.793	0.281	0.871
TiO_2 (na)	0.005	0.350	0.589
Aluminium (d)	0.547	0.436	0.514
Calcium (d)	0.947	0.747	0.072
Iron (d)	0.545	0.989	0.388
Potassium (d)	0.231	0.886	0.486
Magnesium (d)	0.176	0.778	0.753
Manganese (d)	0.840	0.801	0.303

Variable	Climate Zone	Soil Type	Climate zone & Soil Type
Sodium (d)	0.054	0.025	0.227
Phosphorous (d)	0.853	0.616	0.110
Silicon (d)	0.625	0.273	0.683
Titanium (d)	0.001	0.787	0.858
Alkali index	0.254	0.824	0.420

†basis of analysis; ar = as received fuel, d = dry fuel, DAF = dry, ash-free fuel, na= normalised ash. Dark blue cells indicate $p<0.001$; light blue cells $0.001<p<0.05$

Table 8-8: Mean values and assessment of relevance for main effects and interactions identified by structured analysis for poplar leaves (number of analyses if not default)

One Factor Analysis			
Variable	Climate zone		Assessment
	Warm/dry	Warm/ moist	
Default number of analyses	8	3	
BaO, %wt na	0.01	0.03	Unlikely to have operational impact
Na_2O, % wt na	0.22	0.37	Relevant for further study
TiO_2, %wt na	0.02	0.01	Unlikely to have operational impact
Ti, mg/kg dry	10.3	5.4	Unlikely to have operational impact
	Soil Type		
	Light	Medium	
Default number of analyses	6	5	
Na_2O, % wt na	0.33	0.17	Relevant for further study
Na, mg/kg dry	176.6	93.9	Relevant for further study

Two Factor Analysis				
Variable		Climate zone		Assessment
	Soil type	Warm/dry	Warm/moist	
Default number of analyses		4	2	
Ash, %wt dry	Light	9.7	8.5	
	Medium	8.7	9.8 (1)	Relevant for further study
Sb, mg/kg dry	Light	0.098	0.08	Exclude – at or below limit of detection level
	Medium	0.093	0.1 (1)	
As, mg/kg dry	Light	0.098	0.08	Exclude – at or below limit of detection level
	Medium	0.093	0.1 (1)	

8.3 Null hypothesis

Of the many site properties collected for poplar SRF, the following had sufficient variation in the data to be suitable for statistical analysis: planting density, soil classification, age of sampled material, pH and cation exchange capacity (CEC). In this section, planting density and age of the sampled material are considered by correlation analysis (as discussed in Section 2.6.3); the impact of soil classification was investigated in Section 8.2, and the impact of pH and CEC are covered in the correlation analysis, which is discussed in Section 8.4.

The full results of the correlation analysis are presented in Appendix 5, with these tables colour-coded to indicate those correlations (positive or negative) which explain either >50% or >80% of the variability, as discussed in Section 2.6.5. Neither the planting density nor the age of the sampled material of poplar SRF trunks or tops explained a significant proportion of the variation in the selection of feedstock characteristics investigated (see Appendix 11).

8.4 Determining factors

Determining the factors of greatest importance to feedstock characteristics can only be done in a qualitative way by review of the statistical analyses performed. For poplar SRF, the structured factors were climate zone, soil type, harvest time and storage in Study 1 for the trunk and tops and climate zone and soil type in Study 3 for leaves. The other statistical analyses to be considered are the correlations with soil characteristics and the correlations with site information (where these were possible).

Of the four structured factors investigated for their effect on the poplar SRF trunk (including bark), storage had the greatest number of impacts on feedstock characteristics, followed by the harvesting time (Table 8-2). Soil type significantly influenced only a few characteristics and climate zone affected only one. There were however several highly significant two-way interactions which were mainly between storage and harvesting time but also many between climate zone and harvesting time with a couple between climate zone and storage and between soil type and storage. In addition there were a few three-way interactions, mostly involving climate zone, soil type and harvesting time

For the poplar SRF tops, storage had a significant impact on the greatest number of feedstock characteristics (Table 8-4). The next most influential factor was harvesting time. Climate zone and soil type had fewer impacts. There were a very limited number of important two-way interactions, which were mainly between storage and harvesting time with a couple of interactions between storage and climate zone and between harvesting time and climate zone. Although soil type had few main effects it was included in some interactions the other factors, principally climate zone and in a few instances with storage and harvesting time.

In the case of poplar SRF leaves, a number of characteristics were statistically affected by climate zone, with fewer influenced by soil type, whilst the combination of both factors impacted on three characteristics (Table 8-7).

Once these statistically significant effects were screened for their analytical and operational significance, the most influential factor was storage, and to some extent harvest time, on moisture content and consequentially NCV. There is a suggestion that concentrations of some of the macroelements changed (mainly decreasing) on storage for the trunks, but this was not apparent for the tops. For the tops the most interesting observation was a significant increase in dry ash, DAF sulphur, DAF nitrogen and DAF chlorine in freshly harvested material from the second harvest, which was also wetter. The concentrations of a number of macroelements also increased in the second harvest – this is probably a consequence of the higher ash content. However, these changes were not observed for the trunk material. It can be seen that after the tops from the second harvest were stored, the differences between the samples from the two different harvests were not so apparent after storage. It should be noted that, due to the timing of the project, by the time of the second harvest the poplar was in full leaf and so these samples may have contained leaf material (particular in the fresh material).

In the case of leaves, further evaluation of the statistically significant effects suggested that for climate zone only the impacts on sodium are worthy of note as the changes for the other

characteristics were operationally insignificant. The combination of the two factors climate zone and soil type did appear to have some impact on dry ash content.

As discussed in Section 2.6.3, the total variation explained by these structured factors was quantified using REML; the result of this (for all feedstocks) is presented in Appendix 9. This explained ca. 68% and 78% of the total variation in the moisture and net CV of the trunks and tops respectively. In fact this was the highest level of variation explained. Approximately 30-70 % of the variation in the other proximate and ultimate fuel properties could be explained. The explainable variation was lower for the trace elements, macroelements and ash composition than for the major fuel parameters. The leaves are not directly comparable with the trunks and tops as the former contained fewer structured factors. Approximately 44% and 50% of the total variation in sodium content in the poplar SRF leaves and the equivalent oxide in the ash respectively could be explained, together with 30% of the variation in ash content.

Despite the rather limited main effect of soil type, there were occasional strong correlations between individual soil properties and feedstock characteristics. The principal observations for poplar SRF trunks, which included the bark, were:

- Phosphorus in the trunks was negatively related to the silt percentage in the soil (Figure 8-8).
- Cobalt in the trunks was positively related to available nitrogen and available iron in the soil and the soil organic matter (Figure 8-9).

Figure 8-8: Correlation between phosphorous in poplar SRF trunk and silt percentage in dry soil.

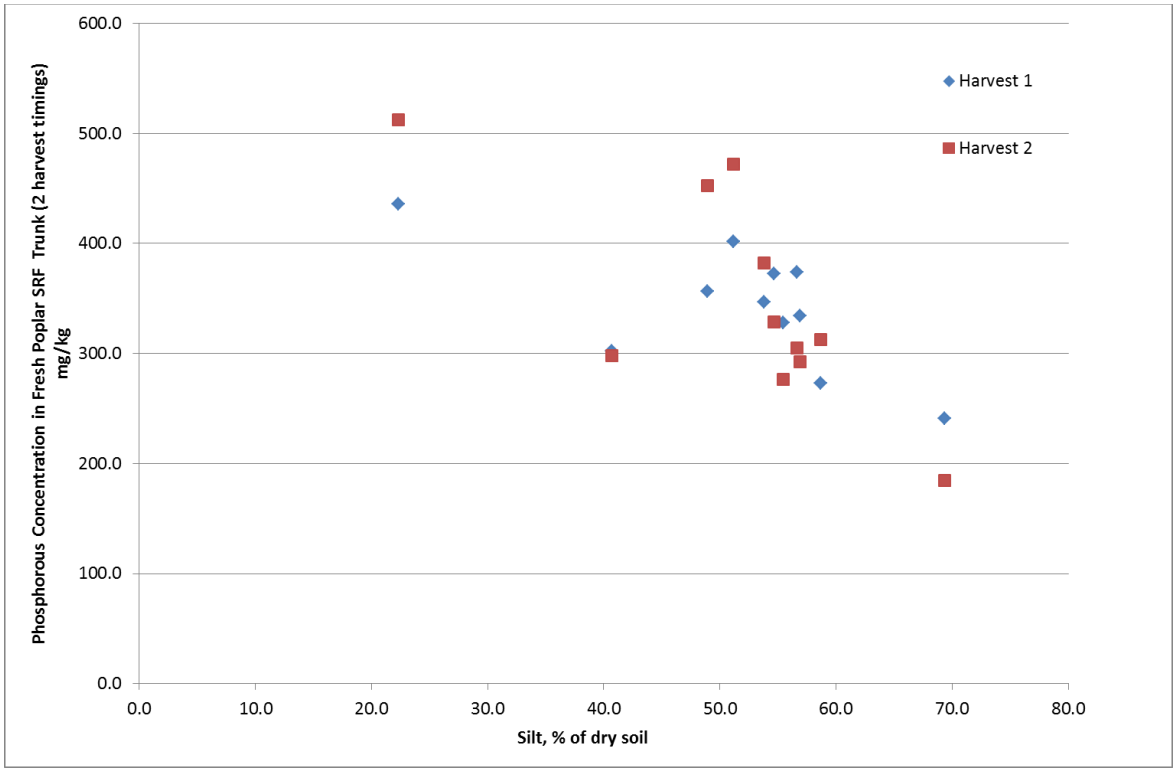
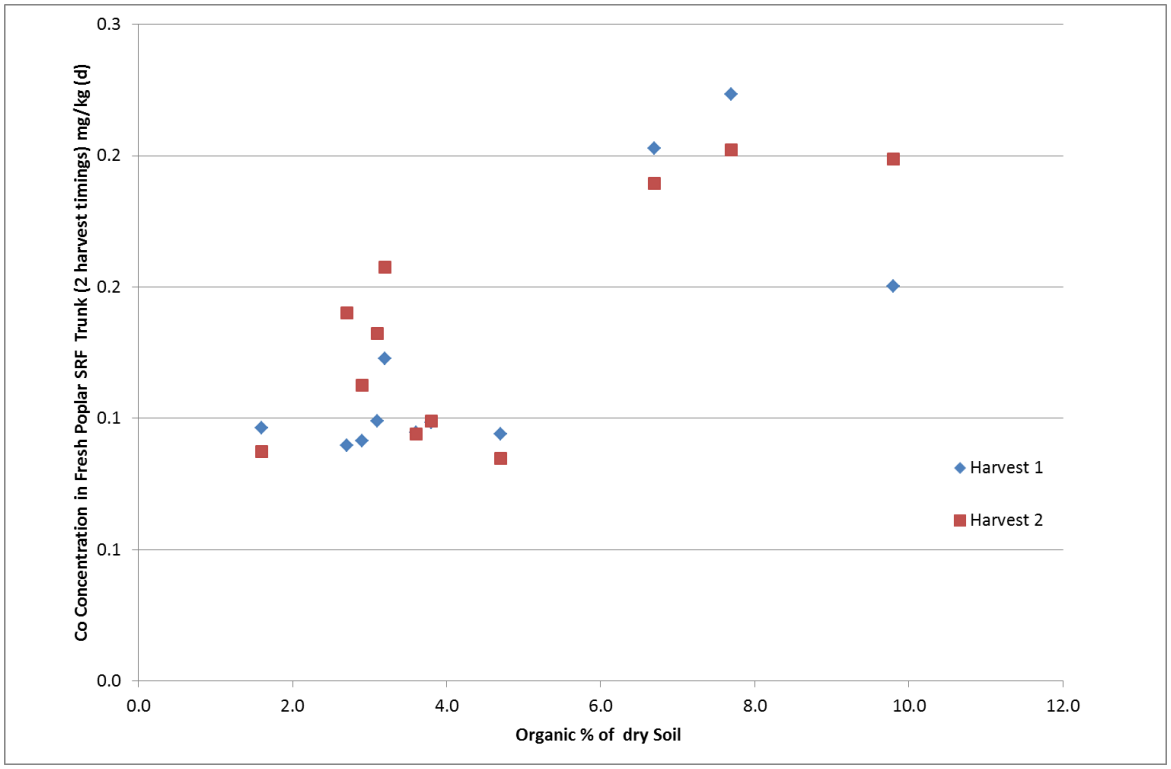


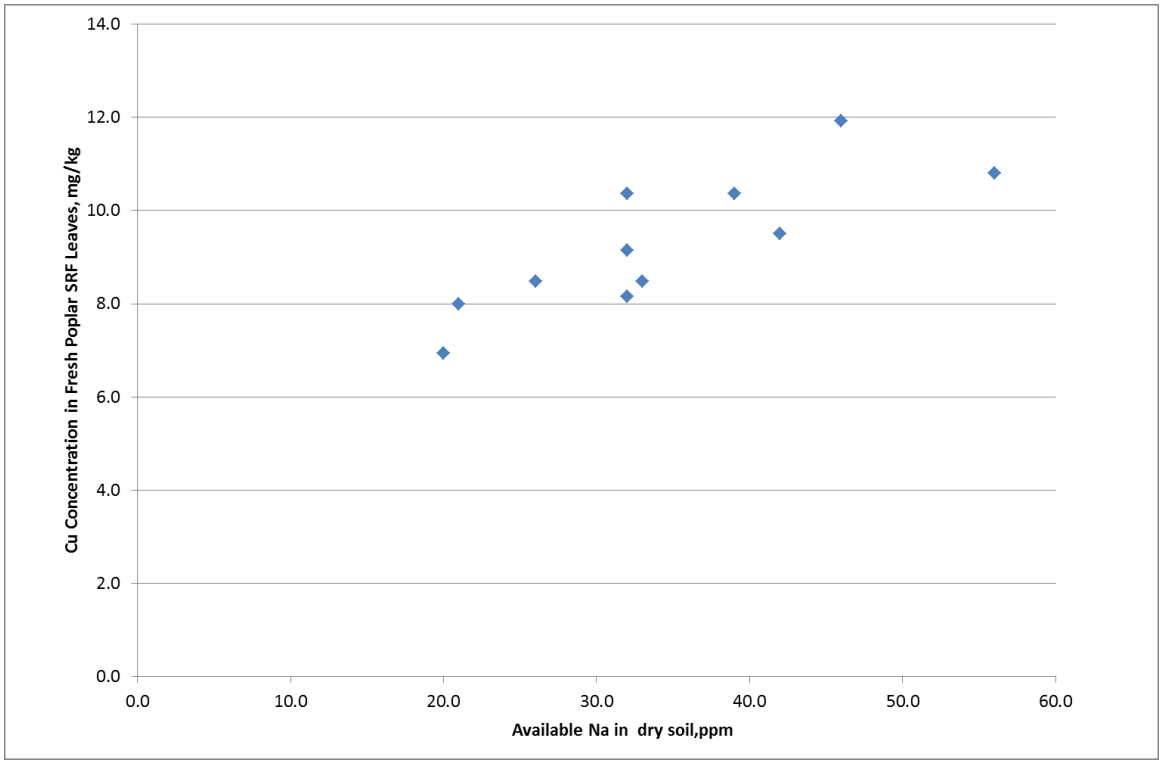
Figure 8-9: Correlation between cobalt in poplar SRF trunk and organic content of soil



The principal observations for poplar SRF leaves were:

- Chromium was strongly positively related to the percentage of sand in the soil and to a lesser extent to soil available phosphorus, manganese, and zinc whereas chromium was strongly negatively related to the silt percentage in the soil.
- Copper in the leaves was positively related to the available sodium (Figure 8-10) and nitrogen in the soil.
- Sodium levels in the ash from poplar leaves was negatively related to available calcium in the soil.
- Phosphorus concentration were positively related to available manganese in the soil.

Figure 8-10: Correlation between copper in the poplar SRF leaves and soil available sodium



Management factors, in this case planting density and the age of the sampled material, were not important determinants of the feedstock characteristics of poplar SRF trunks or tops.

Although three of the sites were identified as having had sewage sludge applied, Table 8-9 shows that the trace element levels within their soils were equivalent to, or lower than, those of the untreated willow sites. It should be noted that all applications were more than 10 years before this exercise. No data on the sewage sludge composition was available.

Table 8-9: Comparison of total soil trace element content for poplar SRF sites with and without sewage sludge treatment

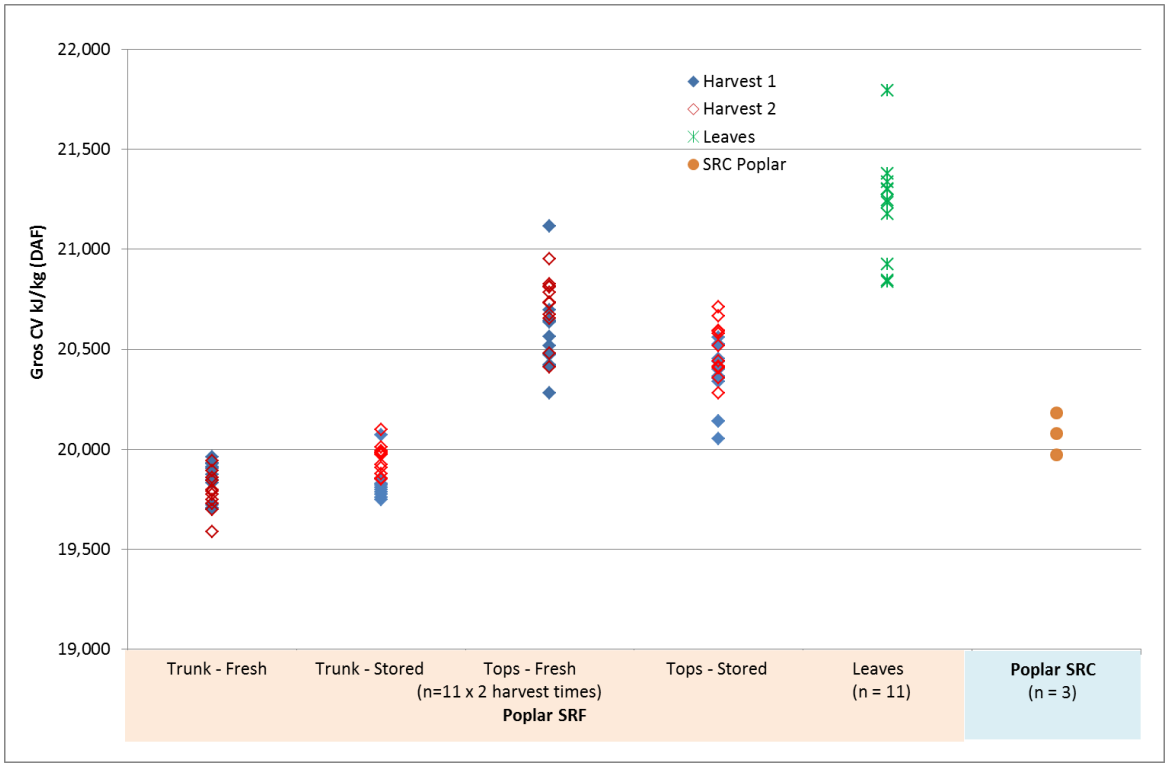
	Element	Cu	Zn	Pb	As	Cd	Hg	Cr
Sewage sludge treated sites	Total concentration in dry soil / Site number	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	090	9.3	43.11	21.29	18.96	0.06	0.16	34.65
	091	16.23	68.05	19.73	12.61	0.12	0.01	39.68
	094	12.42	65.01	24.4	5.5	0.11	0.03	27.87
Average sludge treated soils		12.65	58.72	21.81	12.36	0.10	0.07	34.07
Average non-sludge treated soils		17.60	75.97	27.08	7.61	0.11	0.16	34.92

8.5 Comparison of different plant parts

Leaf samples were taken from eleven sites used in Study 1 when the second harvest was being collected in July. Figure 8-2 has already demonstrated that the moisture content of the poplar SRF leaves was only slightly higher than the poplar SRF samples themselves. However, as was observed for the willow SRC leaves, their DAF Gross CV is higher, due once

again to increased DAF carbon and hydrogen and lower DAF oxygen in the leaves (see Figure 8-11).

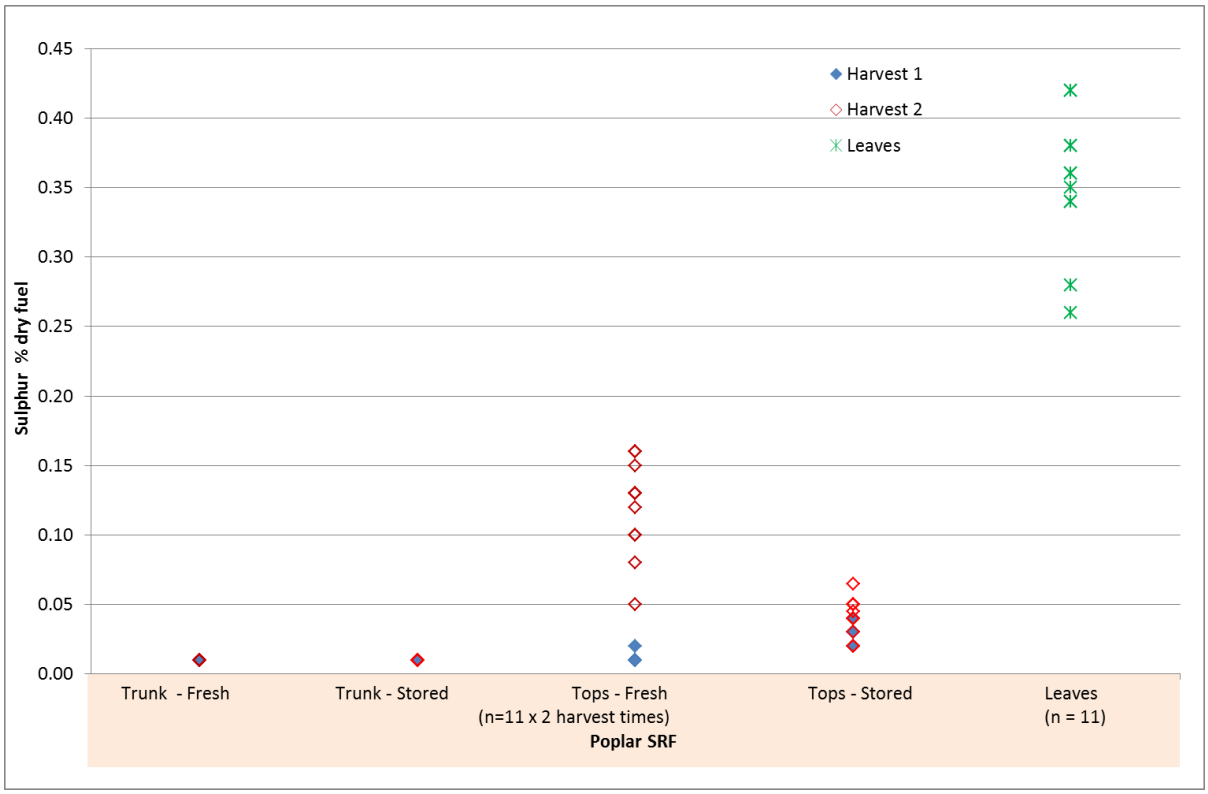
Figure 8-11: Results from the GCV (DAF) analysis of poplar SRF & poplar SRC in study 1, showing harvest time impacts and leaf analysis from study 3



Although the DAF GCV is higher, due to the higher ash and moisture content of the leaves (Figure 8-5), their Net CV is reduced to be lower than the other parts of the poplar that were sampled (Figure 8-3).

In general, the observation of increasing levels of most chemical parameters in the order trunk<tops<leaves can be made. The ash content of the tops is typically 2-3 times that found in the trunk, whilst the concentration in the leaves can be 10 times higher (Figure 8-5). This will result in higher mineral and trace element concentrations in these particular plant parts. Figure 8-7 has previously illustrated the increased dry nitrogen content of the tops and leaves compared to the trunk and sulphur shows similar behaviour (Figure 8-12).

Figure 8-12: Results from the sulphur (d) analysis of poplar SRF in study 1, showing harvest time impacts and leaf analysis from study 3



Again, it is worth highlighting the significant increases of both characteristics; sulphur was undetectable in the trunks, but was determined at approximately 0.05% (dry) in the tops and approximately 0.35% (dry) in the leaves, likewise, the concentrations of nitrogen in the trunk were approximately 0.25% (dry), whilst levels were 4-5 times higher in the tops and 10 times higher in the leaves. Similar large changes are apparent for chlorine and bromine, although much of the bromine data is at the limit of detection, including some leaf samples.

The behaviour of the macroelements in the leaves is also interesting to note, with aluminium (Figure 8-4), iron, silicon and titanium appearing at broadly similar levels in all of the plant parts. However, with the exception of sodium, the majority of the alkali and alkaline earth elements (plus phosphorous) are present at significantly higher levels in the tops and leaves compared to the trunk. Note that plots for all poplar SRF feedstock variables are provided in Appendix 12.

The various influences described above have been collated, focussed on the variables thought in the team's expert opinion to be important in a commercial operational context, and ranked in a qualitative way. Table 8-10 must be treated with caution but nevertheless indicates that feedstock characteristics are not affected in a consistent way by the site properties and crop management. It implies that growers have a reasonable degree of control over many of the most important influences on feedstock properties. For example, the most important factor affecting moisture and NCV, i.e. storage, can be manipulated. Many of the other properties can be adjusted by the choice of the plant part to market and harvest time. The implications for buyers are that consideration must be given to the feedstock characteristics of prime importance in a particular application.

Table 8-10: Factors influencing key feedstock characteristics of poplar SRF ranked in order of decreasing importance.

Variable	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
Moisture % wt (ar)	Storage	Plant part	Climate zone	Soil type	Harvest time
NCV, kJ/kg (ar)	Storage	Plant part	Climate zone	Soil type	Harvest time
Ash, %wt (d)	Plant part	Storage=Harvest time		Soil type	Climate zone
N, %wt (DAF)	Plant part	Storage=Harvest time		Soil type	Climate zone
Sulphur, %wt (DAF)	Plant part	Storage=Harvest time		Soil type	Climate zone
Chlorine, %wt (DAF)	Plant part	Storage=Harvest time		Climate zone	Soil type
Zn, mg/kg (d)	Plant part	Harvest time	Soil type	Storage	Climate zone
Cd, mg/kg (d)	Plant part	Storage	Harvest time	Climate zone	Soil type
Al_2O_3, %wt (na)	Plant part	Harvest time=Climate zone		Storage	Soil type
Fe_2O_3, %wt (na)	Plant part	Harvest time	Climate zone	Storage	Soil type
K_2O, %wt (na)	Plant part	Harvest time	Soil type	Storage	Climate zone
Na_2O, %wt (na)	Plant part	Harvest time	Storage	Soil type	Climate zone
SiO_2, %wt (na)	Plant part	Harvest time	Climate zone	Soil type	Storage
Al, mg/kg (d)	Plant part	Storage	Soil type	Climate zone	Harvest time
K, mg/kg (d)	Plant part	Storage	Harvest time	Climate zone	Soil type
Na, mg/kg (d)	Plant part	Soil type	Harvest time	Storage	Climate zone
Si, mg/kg (d)	Plant part	Harvest time	Storage	Climate zone	Soil type
Alkali Index	Plant part	Harvest time	Storage	Climate zone	Soil type
P, mg/kg (d)	% silt in the soil				

8.6 Comparison of poplar SRC and SRF

Only three samples of poplar SRC were sourced for this project due to limited availability of sites in the UK. As discussed in Section 7, poplar SRC was harvested and analysed as a single entity unlike the poplar SRF which, on harvesting, was separated into trunk and tops for analysis. Additionally, no storage experiments were attempted on the poplar SRC samples. Having so few data points for poplar SRC makes comparison with poplar SRF difficult, but in general its characteristics tend to lie midway between the two datasets for poplar SRF trunks and tops. Figure 8-11, Figure 8-5 and Figure 8-7 illustrate this behaviour for DAF GCV, dry ash and dry nitrogen content respectively. Although not illustrated, the same behaviour pattern was observed for many of the trace and macroelements.

In summary, although very few results were obtained from poplar SRC, the data suggests that it is similar in characteristics to poplar SRF, if both the trunks and top are taken into account.

8.7 Conclusions

Relevant hypotheses are:

- *With the exception of Miscanthus, the feedstocks are differentiated into plant parts that have different functions, e.g. mechanical support versus photosynthesis; therefore we hypothesise that these plant parts will differ in their fuel properties and/or composition.*

The composition of the poplar SRF trunk, tops and leaves clearly demonstrated differences between them, as discussed in Section 8.5. With the exception of sodium, the majority of the alkali and alkaline earth elements (plus phosphorous) were present at significantly higher levels in the tops and leaves compared to the trunk.

- *Feedstock properties will differ depending on the climate the crop is exposed to.* Climate zone had very few main effects on poplar SRF trunks or tops instead interacting with harvest time and occasionally with soil type. For the poplar SRF leaves, the only significant impact of climate zone seen was for sodium.
- *Feedstock properties will differ depending on the soil composition and characteristics of the site.* Soil type had almost no main effects on poplar SRF trunks or tops; however some impacts were seen for poplar SRF leaves.
- *Feedstock properties will differ according to the time of year that the biomass is harvested.* A number of feedstock characteristics did vary with harvest time, though this was more evident in the tops than the trunk. For the tops there was a significant increase in dry ash, DAF sulphur, DAF nitrogen and DAF chlorine in freshly harvested material from the second harvest, which was also wetter (see Figure 8-2 and Figure 8-5). This could be a result of the inclusion of leaf material during the second harvest.
- *Feedstock properties will differ with storage.* Storage was the most influential of the factors investigated in particular affecting moisture content (and hence NCV). The concentrations of some of the macroelements changed (mainly decreasing, with the exception of potassium which increased) on storage for the trunks, but this was not apparent for the tops.

Management factors, in this case planting density and the age of the sampled material, were not important determinants of the feedstock characteristics of poplar SRF trunks or tops.

Correlation analysis between the soil properties and the feedstock characteristics did not identify any strong relationships (positive or negative).

The characteristics of poplar SRC tended to lie midway between poplar SRF trunks and tops e.g. DAF GCV, dry ash and dry nitrogen content and many of the trace and macroelements.

A qualitative ranking of factors affecting the characteristics of poplar SRF implies that growers have a reasonable degree of control over many of the most important influences on feedstock properties. For example, the most important factor affecting moisture and NCV, i.e. storage, can be manipulated. Many of the other properties can be adjusted by the choice of the plant part to market and harvest time. The implications for buyers are that consideration must be given to the feedstock characteristics of prime importance in a particular application. In the case of poplar SRF, the important quality determinants are relatively obvious and reliable product information about plant part, harvest time and storage could be a means of building confidence in the product's suitability for conversion.

9 Spruce SRF

9.1 Introduction

Most use of conifers grown in Britain for fuel is for heat production at a moderate scale, primarily using the lower portion of the stem with the upper stem and side branches being left on site. There is potential to use the resource at a greater scale and for a wider range of conversion technologies. There is also the potential to increase the yield from forestry by using the upper stem and branches as well as (or instead of) the lower stem for bio-energy. At present however this is still a developing market and there is no single approach to harvesting. It is not unrealistic to visualise a situation where different portions of the same tree are used for different markets if the overall value of the product mix justifies the additional cost of the segregation, e.g. bark for mulches; large-dimension straight trunks for construction; stems with smaller diameters and poorer form as well as branches for energy. Bio-energy uses can also be integrated with more conventional processing, for example the outer half-round plank created with a stem is cut into timber with a square or rectangular cross-section (referred to as slab wood) can be sold to energy plants. Consequently it is of interest to consider bark and the wood of the lower stem as two separate fractions and the upper stem with the associated branches and needles as a third fraction; these fractions are referred to as bark, trunk and tops respectively..

Using Sitka spruce SRF as the example species, the variability of coniferous SRF was investigated in Study 1, which looked at the effect of the climate zone (cold/wet, warm/moist), soil type (mineral, organic, peat), harvest time (mid-March, mid- to late June) and storage (no storage or three months' outside storage) on feedstock characteristics. All three plant parts were analysed at both harvest times but, as bark was not analysed after storage, the impact of storage on bark was not tested statistically. Needles were not analysed separately.

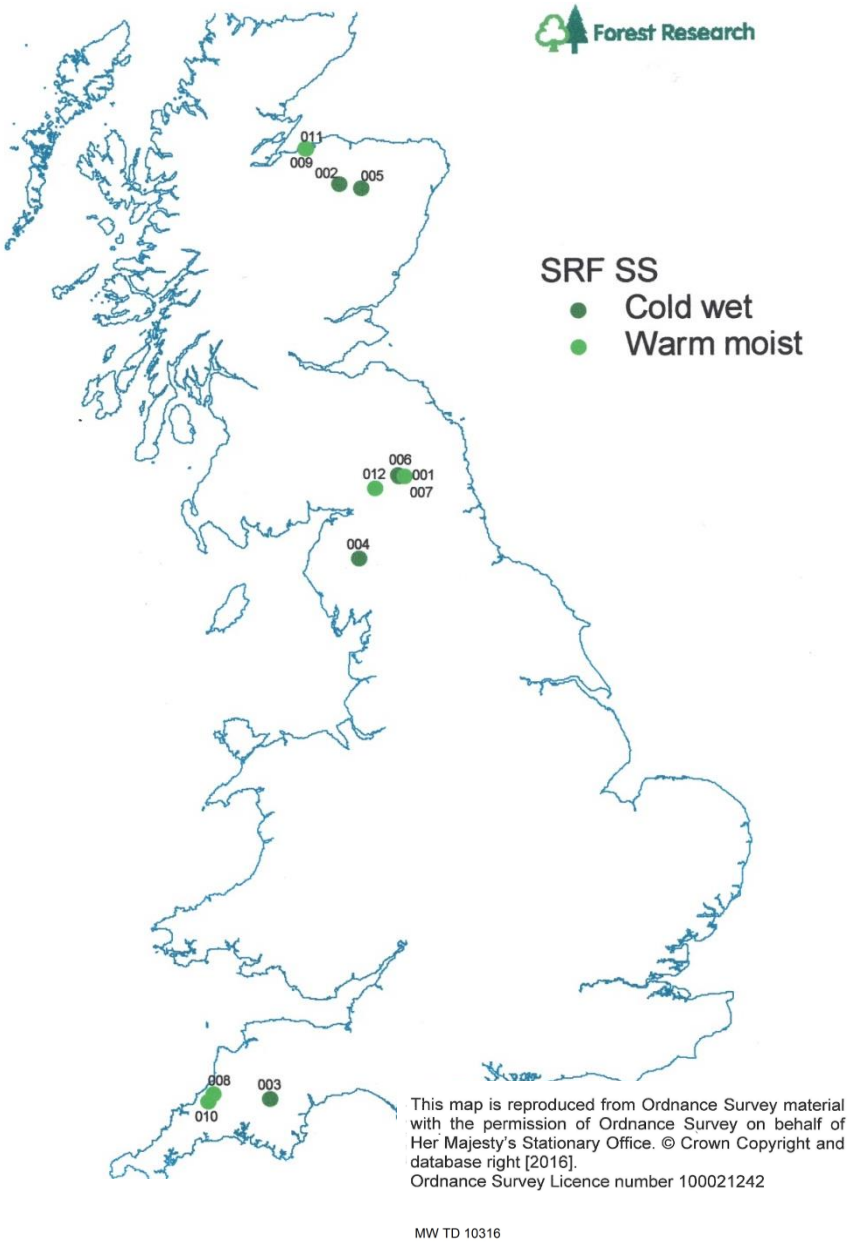
The design of this study also allowed the interactions between the structured factors to be investigated, for example the response to storage could be different in cold/wet climate zones compared to warm/moist climate zones. To investigate the importance of these factors, the original design intended there to be three sites in each combination of climate zone and soil type. A set of 12 sites was identified using GIS, evenly balanced between cold/wet and warm/moist zones (see Figure 9-1 for the geographical location of the sites sampled). The identified sites were further split into having mineral or organic soil classifications (rather than the light, medium, heavy classes used for the other feedstocks). Following the results of the actual soil analysis, three relevant soil categories of measured characteristics were used: mineral, organic and peat (see Figure 3-1 for definitions). Each of the analysed soil types were well represented in warm/moist climate zones, but the soil types were not balanced within the cold/wet climate zone where there were no mineral soils, only one organic soil and five peats (see Figure 9-1). Nevertheless it was possible to complete an analysis of the impact of the four factors (climate zone, soil type, harvest time and storage) on feedstock characteristics. This structured analysis is presented in Section 9.2.

Table 9-1: Number of sites sampled in different combinations of climate zone and soil type

Soil Type / Climate Zone	Mineral	Organic	Peat
Cold/Wet	0	1	5
Warm/Moist	2	2	2

Information on many aspects of each site was collected for the purpose of understanding reasons for any observed differences in the feedstock characteristics. The provenance information included management factors as discussed in Section 3.2.

Figure 9-1: Location of Spruce SRF sampling sites, indicating site numbers used in D4



9.2 Results of structured analysis of climate zone, soil type, harvesting time and storage on feedstock characteristics

For spruce SRF the structured analysis was undertaken separately on the three plant parts examined in this project – trunk, tops (including branches and needles) and bark. The sampling matrix for the trunk and tops included climate zone, soil type, harvest time and storage, whilst bark samples were only taken from the freshly harvested trunks. Note graphs for all feedstock parameters are provided in Appendix 13.

9.2.1 Trunk (excluding bark)

Table 9-2 provides an overview of the impact of the four experimental factors: climate zone (CZ), soil type (ST), harvest time (HT) and storage (STORE) on the trunk, and also their interactions.

The statistics for spruce SRF trunk (de-barked) highlighted many impacts of the four individual structured factors that were investigated. Storage and harvest time had the most impact with just two characteristics influenced by climate zone and none influenced by soil type. A limited number of impacts were also highlighted by the interactions of two of the factors, in particular the combination of harvest time and storage. Few significant impacts from combinations of three and four factors were observed.

Table 9-2: Structured factor analysis of spruce SRF trunk wood

Variable (analysis basis)†	CZ	ST	HT	STORE	CZ & ST	CZ & HT	ST & HT	CZ & STORE	ST & STORE	HT & STORE	CT & ST & HT	CZ & ST& STORE	CZ & HT & STORE	ST & HT & STORE	CZ & ST & HT& STORE
Moisture (ar)	0.845	0.617	0.136	0.000	0.450	0.998	0.979	0.554	0.453	0.110	0.822	0.363	0.459	0.597	0.819
Net calorific value (ar)	0.866	0.618	0.160	0.000	0.423	0.955	0.981	0.520	0.449	0.105	0.828	0.400	0.426	0.605	0.861
Ash content (d)	0.829	0.451	0.033	0.017	0.980	0.062	0.275	1.000	0.439	0.000	0.335	0.641	0.287	0.887	0.276
Volatile matter (DAF)	0.319	0.865	0.144	0.556	0.087	0.043	0.978	0.118	0.743	0.556	0.554	0.419	0.370	0.741	0.562
Gross calorific value (DAF)	0.346	0.999	0.788	0.094	0.263	0.144	0.952	0.199	0.659	0.295	0.968	0.126	0.742	0.878	0.832
Carbon (DAF)	0.562	0.937	0.001	0.000	0.078	0.562	0.923	0.968	0.587	0.001	0.857	0.186	0.741	0.953	0.043
Hydrogen (DAF)	0.366	0.752	0.338	0.000	0.229	0.722	0.954	0.529	0.924	0.031	0.131	0.038	0.147	0.822	0.091
Nitrogen (DAF)	0.773	0.699	0.085	0.048	0.244	0.848	0.672	0.483	0.473	0.000	0.075	0.628	0.848	0.447	0.130
Sulphur (DAF)	0.965	0.940	0.038	0.034	0.353	0.918	0.957	0.928	0.954	0.033	0.359	0.338	0.943	0.947	0.301
Chlorine (DAF)	0.006	0.072	0.240	0.695	0.272	0.050	0.385	0.695	0.081	0.050	0.464	0.010	0.240	0.072	0.003
Barium (d)	0.175	0.849	0.001	0.000	0.528	0.403	0.958	0.044	0.932	*	0.484	0.144	*	*	*
Chromium (d)	0.398	0.692	0.219	0.042	0.461	0.560	0.398	0.541	0.614	*	0.501	0.488	*	*	*
Cobalt (d)	0.522	0.869	0.916	0.463	0.550	0.090	0.309	0.855	0.961	*	0.520	0.932	*	*	*
Copper (d)	0.877	0.382	0.111	0.030	0.067	0.896	0.916	0.525	0.986	*	0.586	0.014	*	*	*
Molybdenum (d)	0.029	0.105	0.005	0.009	0.250	0.830	0.770	0.709	0.904	*	0.547	0.486	*	*	*
Nickel (d)	0.620	0.617	0.042	0.952	0.376	0.448	0.804	0.473	0.992	*	0.818	0.023	*	*	*
Vanadium (d)	0.880	0.445	0.053	0.019	0.336	0.613	0.754	0.537	0.731	*	0.825	0.777	*	*	*
Zinc (d)	0.328	0.066	0.008	0.017	0.841	0.858	0.773	0.070	0.853	*	0.850	0.043	*	*	*
Cadmium (d)	0.849	0.719	0.555	0.122	0.866	0.808	0.840	0.185	*	*	0.902	*	*	*	*
Lead (d)	0.549	0.669	0.066	0.837	0.552	0.604	0.622	0.726	*	*	0.761	*	*	*	*
Al_2O_3 (na)	0.837	0.901	0.306	0.021	0.008	0.571	0.794	0.918	0.905	*	0.661	0.014	*	*	*
BaO (na)	0.458	0.769	0.257	0.045	0.593	0.811	0.544	1.000	0.737	*	0.370	0.134	*	*	*
$CaCO_3$ (na)	0.293	0.992	0.061	0.198	0.199	0.765	0.423	0.612	0.618	*	0.729	0.506	*	*	*
Fe_2O_3 (na)	0.220	0.661	0.343	0.006	0.188	0.023	0.433	0.010	0.530	*	0.188	0.547	*	*	*
K_2O (na)	0.947	0.846	0.119	0.001	0.784	0.156	0.399	0.606	0.915	*	0.395	0.856	*	*	*

Variable (analysis basis)†	CZ	ST	HT	STORE	CZ & ST	CZ & HT	ST & HT	CZ & STORE	ST & STORE	HT & STORE	CT & ST & HT	CZ & ST& STORE	CZ & HT & STORE	ST & HT & STORE	CZ & ST & HT& STORE
MgO (na)	0.228	0.814	0.001	0.011	0.961	0.557	0.515	0.746	0.887	*	0.554	0.203	*	*	*
Mn_3O_4 (na)	0.936	0.934	0.057	0.079	0.665	0.574	0.622	0.380	0.905	*	0.636	0.710	*	*	*
Na_2O (na)	0.552	0.677	0.011	0.598	0.886	0.924	0.904	0.497	0.443	*	0.443	0.469	*	*	*
P_2O_5 (na)	0.236	0.175	0.827	0.000	0.877	0.321	0.783	0.745	0.955	*	0.828	0.603	*	*	*
SiO_2 (na)	0.639	0.810	0.031	0.003	0.782	0.876	0.782	0.223	0.724	*	0.564	0.332	*	*	*
TiO_2 (na)	0.378	0.992	0.413	0.874	0.942	0.712	0.395	0.626	0.938	*	0.671	0.847	*	*	*
Aluminium (d)	0.698	0.510	0.187	0.649	0.066	0.917	0.727	0.993	0.980	*	0.414	0.116	*	*	*
Calcium (d)	0.316	0.296	0.034	0.000	0.506	0.066	0.581	0.380	0.644	*	0.183	0.818	*	*	*
Iron (d)	0.674	0.920	0.148	0.001	0.831	0.452	0.779	0.580	0.603	*	0.988	0.815	*	*	*
Potassium (d)	0.788	0.532	0.007	0.000	0.678	0.132	0.314	0.567	0.385	*	0.331	0.602	*	*	*
Magnesium (d)	0.772	0.634	0.264	0.000	0.765	0.109	0.728	0.662	0.668	*	0.130	0.626	*	*	*
Manganese (d)	0.961	0.901	0.181	0.003	0.637	0.854	0.771	0.809	0.785	*	0.413	0.883	*	*	*
Sodium (d)	0.643	0.801	0.039	0.004	0.707	0.776	0.783	0.279	0.911	*	0.906	0.432	*	*	*
Phosphorous (d)	0.923	0.157	0.071	0.008	0.947	0.039	0.563	0.600	0.781	*	0.176	0.822	*	*	*
Silicon (d)	0.685	0.858	0.028	0.000	0.811	0.840	0.778	0.866	0.653	*	0.959	0.662	*	*	*
Titanium (d)	0.773	0.716	0.184	0.059	0.962	0.693	0.647	0.332	0.572	*	0.980	0.938	*	*	*
Alkali index	0.793	0.517	0.005	0.000	0.679	0.137	0.298	0.584	0.374	*	0.333	0.612	*	*	*

†basis of analysis; ar = as received fuel, d = dry fuel, DAF = dry, ash-free fuel, na= normalised ash. * Indicates not included in structured analysis. Antimony, arsenic, mercury and bromine were not included in the structured analysis due to limits of detection. Dark blue cells indicate $p<0.001$; light blue cells $0.001<p<0.05$

Each feedstock characteristic identified in the statistical analysis was reviewed according to the measured mean values in relation to the analytical limits of detection, its analytical error, and operational significance (see Section 2.6.4 for further explanation). Table 9-3 and Table 9-4 show how each of the feedstock characteristics was assessed; those that remained following this screening step are not only statistically significant but also analytically and operationally significant and warranted further consideration.

From this structured analysis it is seen that storage has a large impact on moisture content on the trunk material; NCV is also strongly influenced as a consequence, as shown in Figure 9-2 and Figure 9-3.

Figure 9-2: Results from the moisture analysis of spruce SRF

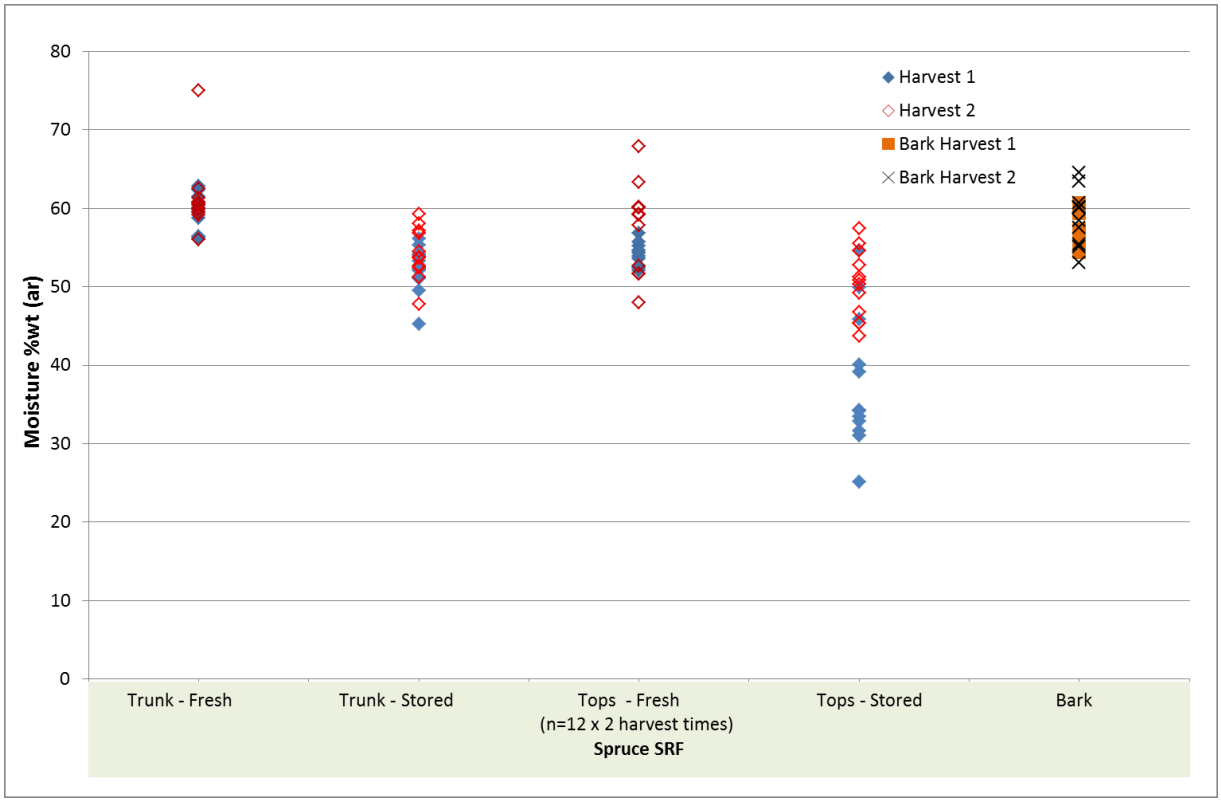


Table 9-3: Mean values and assessment of relevance for interactions identified by structured analysis for spruce SRF trunk (number of analyses if not default)

One variable analysis			
Parameter	Storage		Assessment
	Fresh	Stored	
Default number of observations	24	12	
Moisture, %wt (ar)	60.0 (23)	53.2 (24)	Relevant for further study
NCV kJ/kg (ar)	6019 (23)	7479 (24)	Relevant for further study
Ba, mg/kg (d)	16.27	14.45	Unlikely to have operational impact
Cr, mg/kg (d)	0.12 (23)	0.10	Unlikely to have operational impact
Cu, mg/kg (d)	1.50 (23)	2.33	Unlikely to have operational impact
Mo, mg/kg (d)	0.02	0.02	Unlikely to have operational impact
V, mg/kg (d)	0.04 (23)	0.03	Unlikely to have operational impact
Zn, mg/kg (d)	8.22	7.82	Unlikely to have operational impact
Al_2O_3 (na)	2.07 (23)	4.21	Relevant for further study
BaO (na)	0.55	0.59	Unlikely to have operational impact
Fe_2O_3 (na)	1.22 (23)	0.92	Relevant for further study
K_2O (na)	20.11 (23)	17.82	Relevant for further study
MgO (na)	7.53	7.73	Unlikely to have operational impact
P_2O_5 (na)	6.29	7.69	Relevant for further study
SiO_2 (na)	5.85 (23)	4.49	Relevant for further study
Ca, mg/kg (d)	777.3	527.5	Relevant for further study
Fe, mg/kg (d)	43.6	15.9	Relevant for further study
K, mg/kg (d)	634.6	391.2	Relevant for further study
Mg, mg/kg (d)	163	114	Unlikely to have operational impact
Mn, mg/kg (d)	62.6	46.0	Relevant for further study
Na, mg/kg (d)	11.2	6.7	Relevant for further study
P, mg/kg (d)	104.8	86.4	Relevant for further study
Si, mg/kg (d)	135.2	55.8	Relevant for further study
Alkali Index	0.039	0.024	Relevant for further study
	Harvest Time		
	1	2	
Default number of observations	24	12	
C, %wt (DAF)	50.33	50.69 (24)	Unlikely to have operational impact
S, %wt (DAF)	0.01	0.01 (23)	Limit of detection level
Ba, mg/kg (d)	17.00	13.01	Unlikely to have operational impact
Mo, mg/kg (d)	0.02	0.02	Limit of detection level
Ni, mg/kg (d)	0.15	0.10	Unlikely to have operational impact
Zn, mg/kg (d)	8.57	7.13	Unlikely to have operational impact
MgO, %wt (na)	7.20	8.39	Relevant for further study
Na_2O, %wt (na)	0.37 (23)	0.27	Relevant for further study
SiO_2, %wt (na)	6.12 (23)	3.98	Relevant for further study
Ca, mg/kg (d)	748.1	586.0	Relevant for further study
K, mg/kg (d)	626.4	407.7	Relevant for further study
Na, mg/kg (d)	11.8	5.4	Relevant for further study
Si, mg/kg (d)	136.3	53.7	Relevant for further study
Alkali Index	0.038	0.025	Relevant for further study

Parameter	Climate Zone		Assessment
	Cold/wet	Warm/ moist	
Cl, %wt (DAF)	0.01 (24)	0.01 (24)	Limit of detection level
Mo, mg/kg (d)	0.02 (18)	0.02 (18)	Limit of detection level

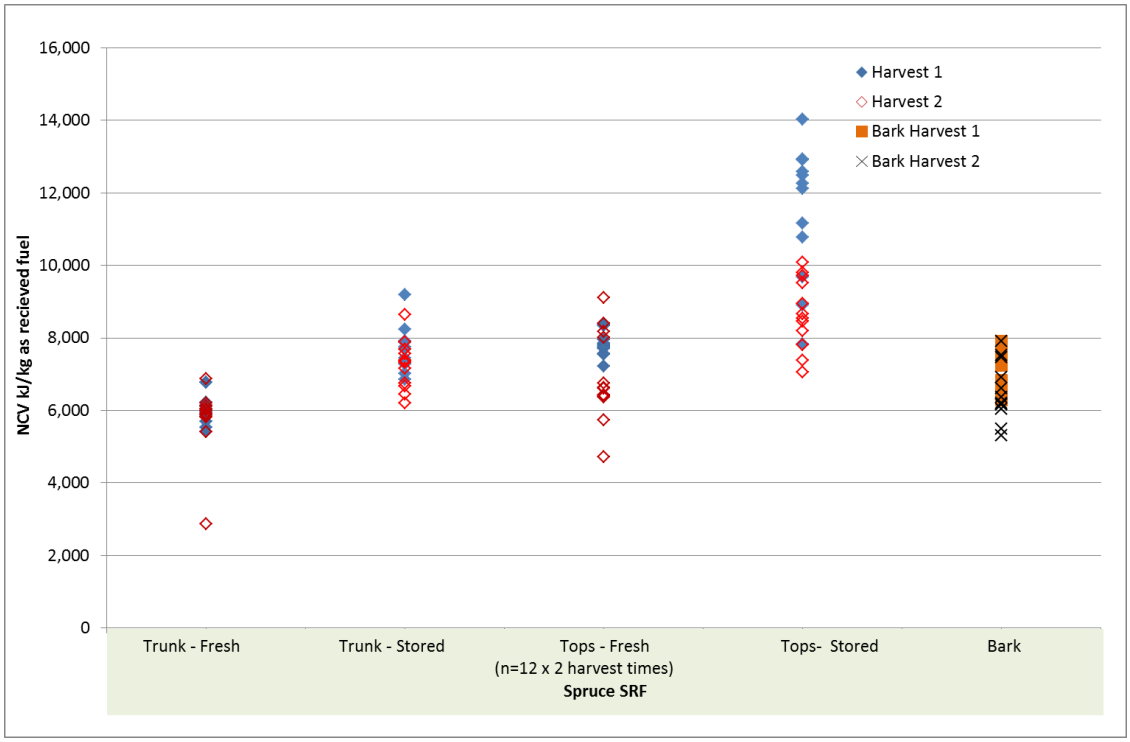
Two Variable analysis				
Parameter	Climate zone / Soil type	Cold/wet	Warm/ moist	Assessment
Al_2O_3, %wt (na)	Mineral	* (0)	2.55 (5)	
	Organic	5.04 (3)	1.32 (6)	
	Peat	2.23 (15)	4.80 (6)	Relevant for further study
	Climate zone / Harvest time	Cold/wet	Warm/ moist	
Default number of observations		12	12	
Volatile matter, %wt (DAF)	1	84.6	84.4	
	2	84.5	85.0	Repeatability of analysis
Fe_2O_3, %wt (na)	1	1.17 (11)	1.16	
	2	1.47 (6)	0.58 (6)	Relevant for further study
P, mg/kg (d)	1	98.3	115.0	
	2	101.8 (6)	63.6 (6)	Relevant for further study
	Harvest time / Storage	1	2	
Default number of observations		12	12	
Ash, %wt (d)	Fresh	0.6	0.3	
	Stored	0.3	0.4	Relevant for further study
C, %wt (DAF)	Fresh	49.88	50.59	Unlikely to have operational impact
	Stored	50.77	50.80	
H, wt (DAF)	Fresh	6.24	6.20	Unlikely to have operational impact
	Stored	6.15	6.16	
N, %wt (DAF)	Fresh	0.31	0.21	
	Stored	0.20	0.26	Relevant for further study
Sulphur, %wt (DAF)	Fresh	0.01	0.01	
	Stored	0.01	0.01 (11)	Limit of detection level

Table 9-4: Mean values and assessment of relevance for interactions identified by structured analysis for spruce SRF trunk cont. (number of analyses if not default)

Three variable analysis								
	Climate zone	Cold/wet			Warm/moist			Assessment
	Soil Type / Storage	Mineral	Organic	Peat	Mineral	Organic	Peat	
Default number of analyses	Fresh	0	2	10	4	4	4	
	Stored	0	1	5	2	2	2	
H, %wt (DAF)	Fresh	*	6.14	6.233	6.225	6.238	6.203	Unlikely to have operational impact
	Stored	*	6.15 (2)	6.14 (10)	6.18 (4)	6.145(4)	6.17 (4)	
Cl , %wt (DAF)	Fresh	*	0.01	0.01	0.01	0.02	0.01	Limit of detection level
	Stored	*	0.01 (2)	0.01 (10)	0.01 (4)	0.01 (4)	0.02	
Cu, mg/kg (d)	Fresh	*	1.19	1.65	0.91	1.11	2.13	Unlikely to have operational impact
	Stored	*	3.42	2.05	2.05	0.99	4.13	
Ni , mg/kg (d)	Fresh	*	0.09	0.15	0.1	0.09	0.15	Unlikely to have operational impact
	Stored	*	0.22	0.14	0.11	0.07	0.26	
Zn, mg/kg (d)	Fresh	*	5.25	9.74	6.35	6.37	9.65	Unlikely to have operational impact
	Stored	*	6.57	7.90	6.48	6.06	11.32	
Al_2O_3, %wt (na)	Fresh	*	5.85	2.62	3.03	1.11	4.80	Relevant for further study
	Stored	*	3.42	1.46	0.64	1.74	4.78	

Four variable analysis														
Parameter	Climate zone	Cold/wet						Warm/moist						Assessment
	Soil type	Mineral		Organic		Peat		Mineral		Organic		Peat		
	Harvest time / Storage	1	2	1	2	1	2	1	2	1	2	1	2	
Default number of analyses		0	0	1	1	5	5	2	2	2	2	2	2	
C, %wt (DAF)	Fresh	*	*	50.5	50.6	49.8	50.6	50.1	50.6	49.3	50.4	50.1	50.7	Unlikely to have operational impact
	Stored	*	*	50.8	51.1	50.9	50.7	50.6	50.7	50.9	50.8	50.6	50.9	
Cl, wt% (DAF)	Fresh	*	*	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.01	Limit of detection level
	Stored	*	*	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	

Figure 9-3: Results from the Net Calorific Value analysis of spruce SRF



Storage also appears to affect the dry ash content and hence the levels of a number of macroelements to some extent, particularly from the first harvest, including aluminium, iron, potassium, phosphorous and silicon (and their respective oxides in ash), their concentrations tending to show a decrease on storage. Note that trace elements were only analysed on the stored material from harvest 1. Figure 9-4 illustrates the decrease in dry ash content after storage (notable only for the first harvest), whilst the reduction in silicon content is evident from Figure 9-5. A reduction during storage in the dry ash content and many macronutrients of trunks harvested in spring but not summer is not easy to explain but may be associated with the spring mobilisation of nutrients in the woody material which is normally redistributed to the distal parts of the shoots to support new needle growth. In this mobile form the macronutrients could be susceptible to wash out, whereas at the second harvest internal redistribution had been completed, macronutrients were no longer in a mobile form and therefore did not reduce during storage. Note that the reduction in ash and many macronutrients in tops with storage is consistent with loss of needles – during drying the abscission layer at the base of the needle weakens with the result that needles are easily detached to the extent that they can fall off or be washed off.

Figure 9-4: Results from the ash analysis of spruce SRF

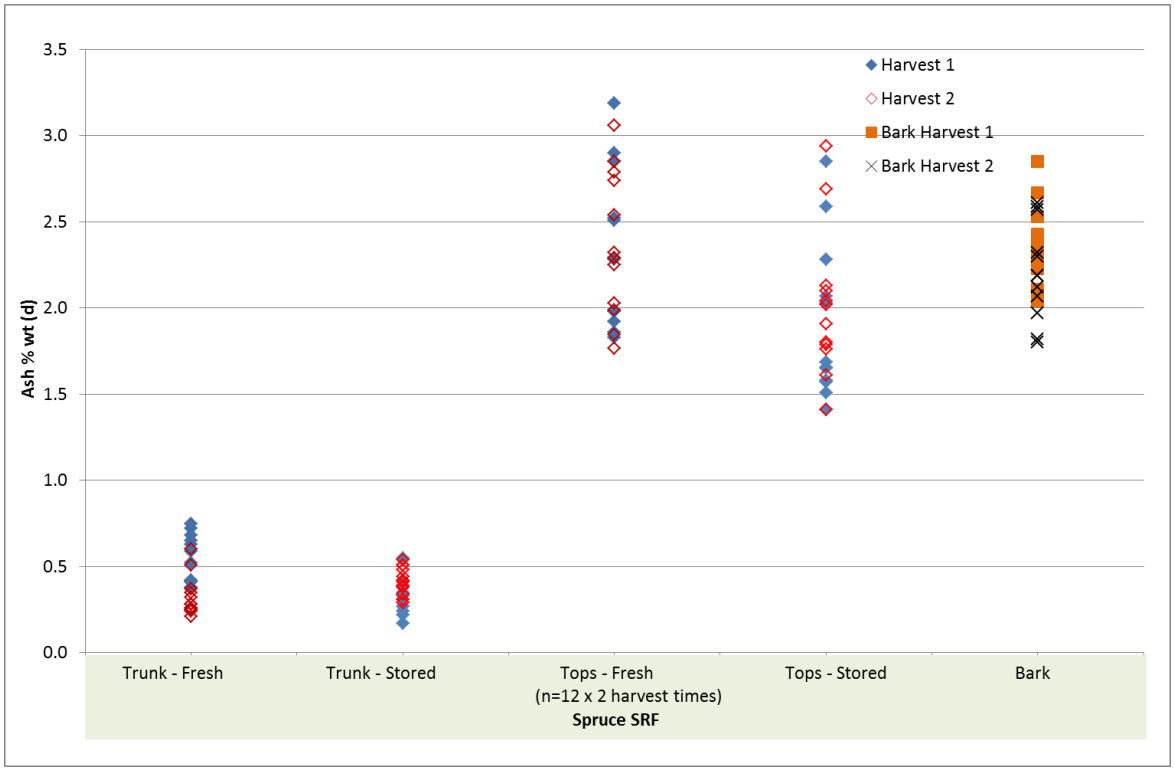
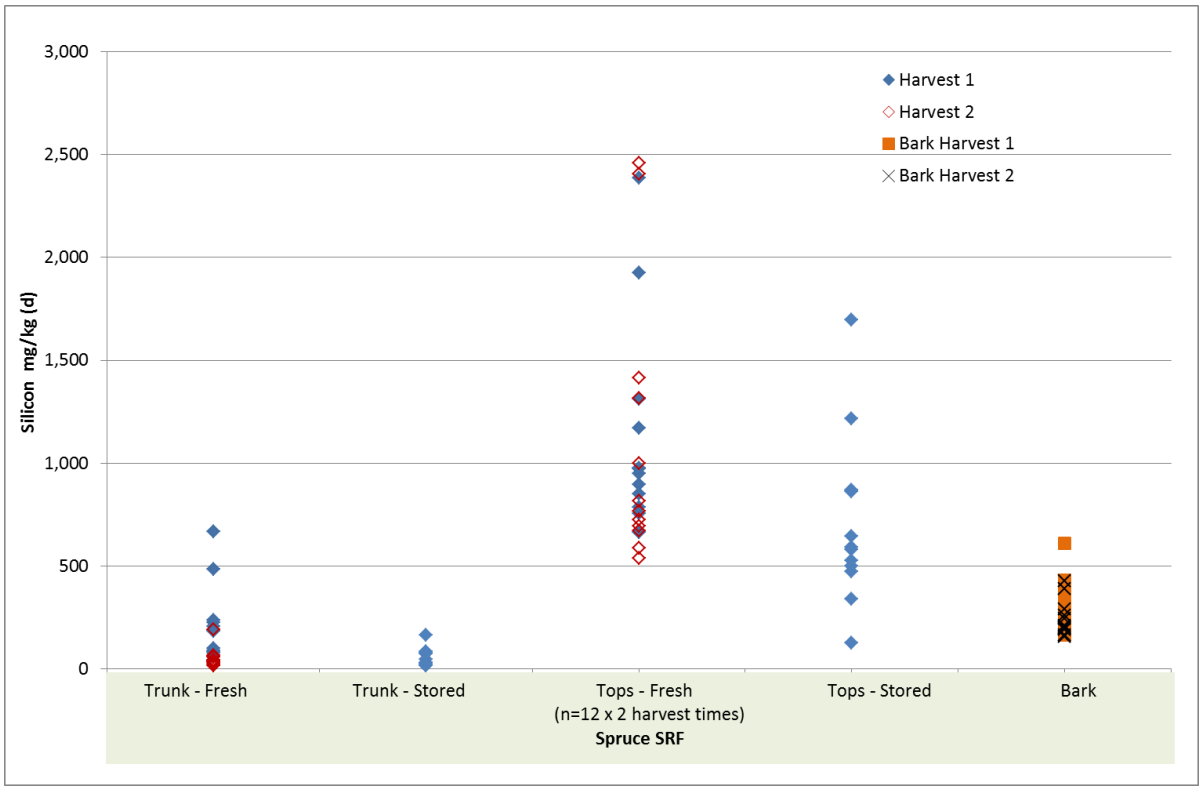


Figure 9-5: Results from the silicon analysis of spruce SRF (note – silicon in fuel is back calculated from ash oxide composition)



It is judged that the other highlighted impacts from storage can be disregarded as the changes are operationally insignificant (see Table 9-3 and Table 9-4).

Although a number of impacts were highlighted for harvest time for the spruce SRF trunks, closer inspection suggests that most of the changes can be disregarded, although again there are indications that the levels of a number of macroelements, including sodium, silicon, calcium and potassium are lower in samples taken from the second harvest. The data for silicon have already been shown in Figure 9-5, whilst Figure 9-6 shows similar behaviour for potassium.

The structured analysis identified two impacts from climate zone, but both can be disregarded as all the analysis data was at the limit of detection. Finally, no impacts were highlighted as a result of soil type.

The six possible two-way combinations of the structured factors only identified a handful of impacts, mainly from the interaction of harvest time & storage. For this particular combination, small changes in ash content were apparent and although the second harvest appears to have a lower ash content overall, on storage the ash content decreased for the first harvest samples and increased slightly for the second harvest (see Figure 9-4). A similar scenario exists for the dry nitrogen content – see Figure 9-7.

Figure 9-6: Results from the potassium analysis of spruce SRF (note – potassium in fuel is back calculated from ash oxide composition)

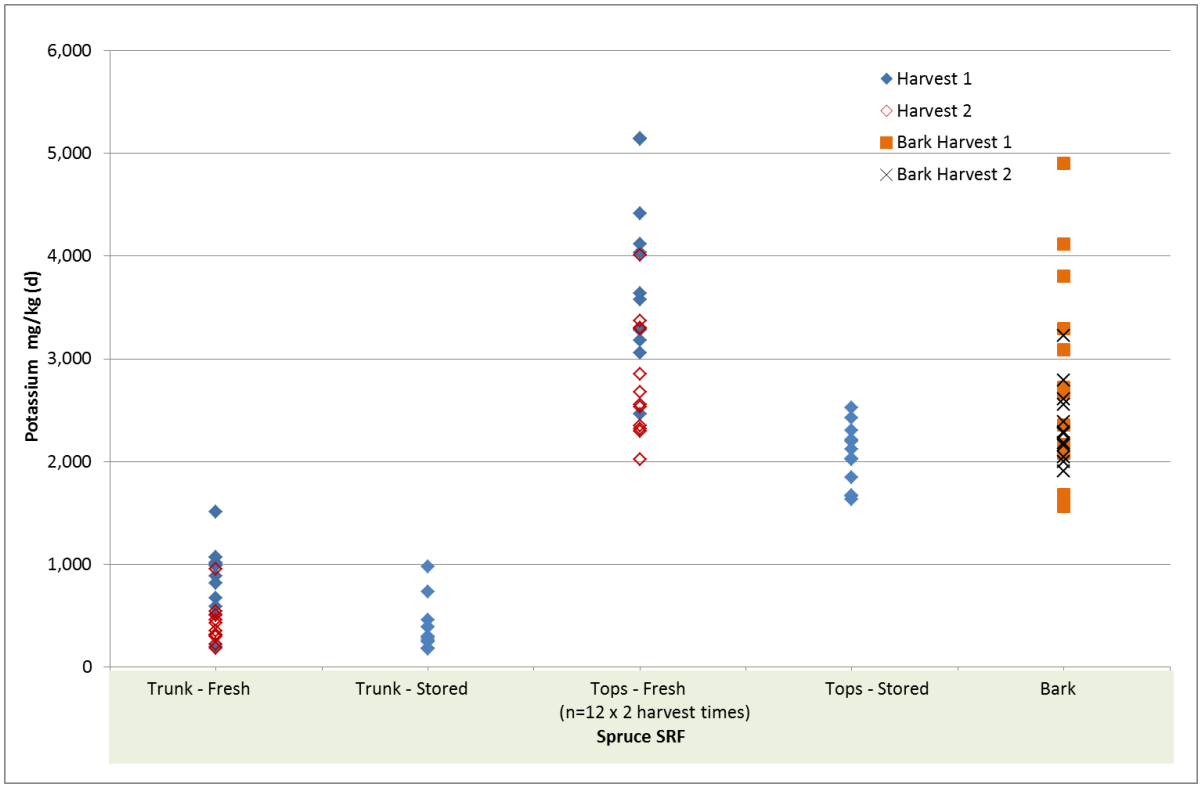
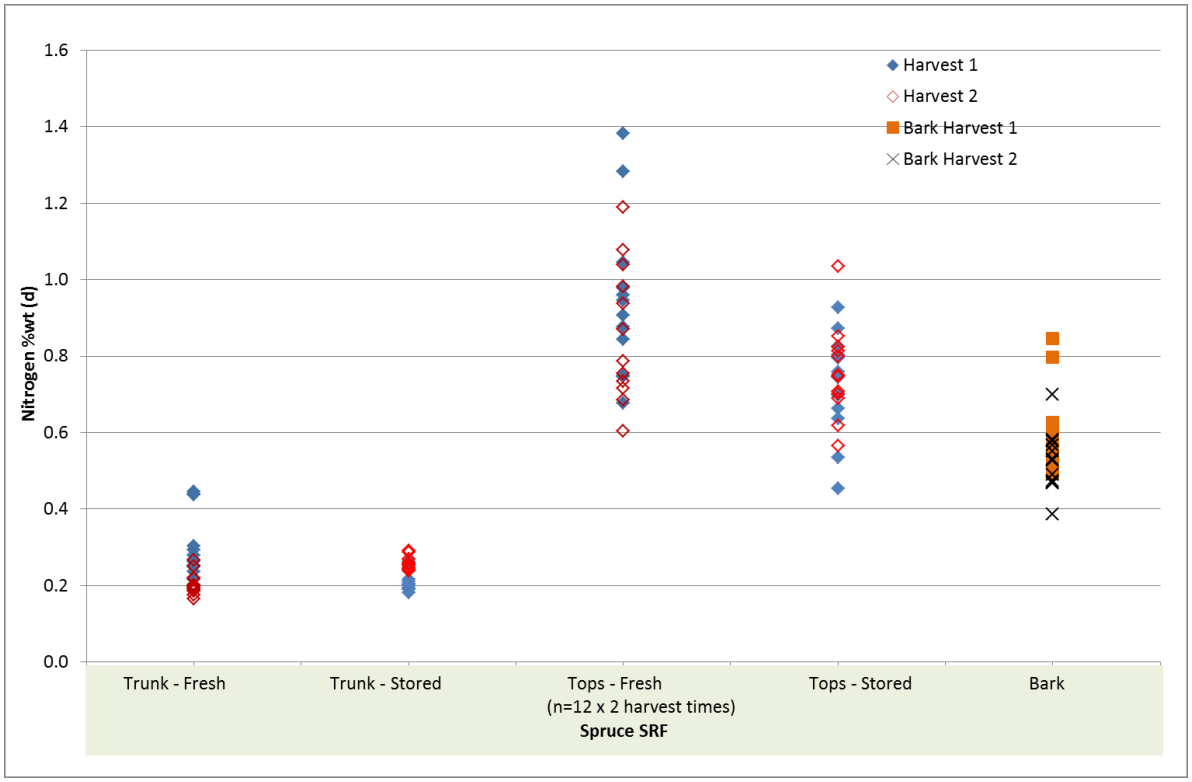


Figure 9-7: Results from the nitrogen analysis of spruce SRF



Other impacts can be ignored as either operationally insignificant or where the data were less than the analytical repeatability.

The combinations of climate zone & storage and climate zone & harvest time highlighted a total of five impacts, of which those for Fe_2O_3 in ash and phosphorous were judged to be worthy of comment. The stored or second harvest samples from the warm/moist climate zone appear to have lower Fe_2O_3 concentrations. The combination of climate zone & soil type only impacted on Al_2O_3 in ash, although the data across the three soil types and two climate zones was difficult to interpret. The combination of soil type and storage had no impacts.

Of the 'three-way' interactions, only the combination of climate zone & soil type & storage has any impacts, although all of these, with the exception of Al_2O_3 in ash, were either operationally insignificant or the data was less than the limit of detection. As was the case with the climate zone & soil type impact discussed above, the Al_2O_3 data were highly variable and difficult to interpret, particularly given the lack of samples for some of the combinations. The two impacts of the 'four-way' interaction of all four factors can both be ignored either as being operationally insignificant (for carbon on a DAF basis) or as being less than the limit of detection (for chlorine on a DAF basis).

9.2.2 Tops (including branches)

The statistics for spruce SRF tops show a similar spread of impacts to that for the trunk parts, with storage and harvest time having the most impact, just one characteristic influenced by climate zone and none influenced by soil type (Table 9-5). A limited number of impacts were also highlighted by the interactions of two of the factors, in particular the combination of harvest time and storage. The number of significant impacts from combinations of three factors and finally the combination of all four factors were lower still. These statistically significant effects were reviewed for their analytical and operational significance to identify ones that warranted further consideration.

Storage influenced the moisture content of the tops – notably more so for the first harvest where moisture content decreased by around 15 percentage points during storage; the NCV was increased as a consequence – see Figure 9-2 and Figure 9-3. The stored material was also somewhat lower on average in dry ash content (Figure 9-4). The stored material also indicated clear decreases in nitrogen (see Figure 9-7), with chlorine content showing similar behaviour. Of the other impacts, only the changes in calcium and potassium (see Figure 9-6) and their respective oxides in ash were judged to be worthy of comment, and both decreased slightly in the stored material. The trace element lead is also highlighted as this showed an increase in concentration from fresh to stored material as illustrated in Figure 9-8. The tops from certain sites were noted to have consistently higher lead content than others, and some relationship with lead content in soil may be observed (see Figure 9-9).

Figure 9-8: Results from the lead analysis of spruce SRF

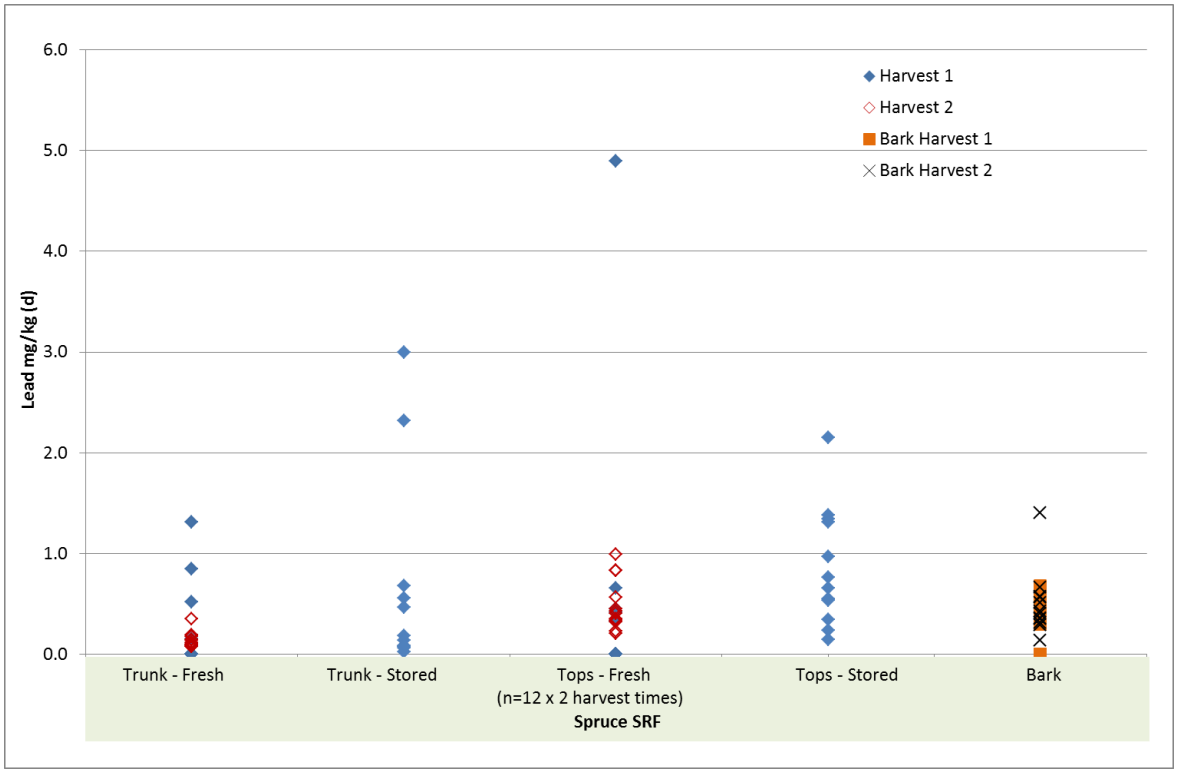
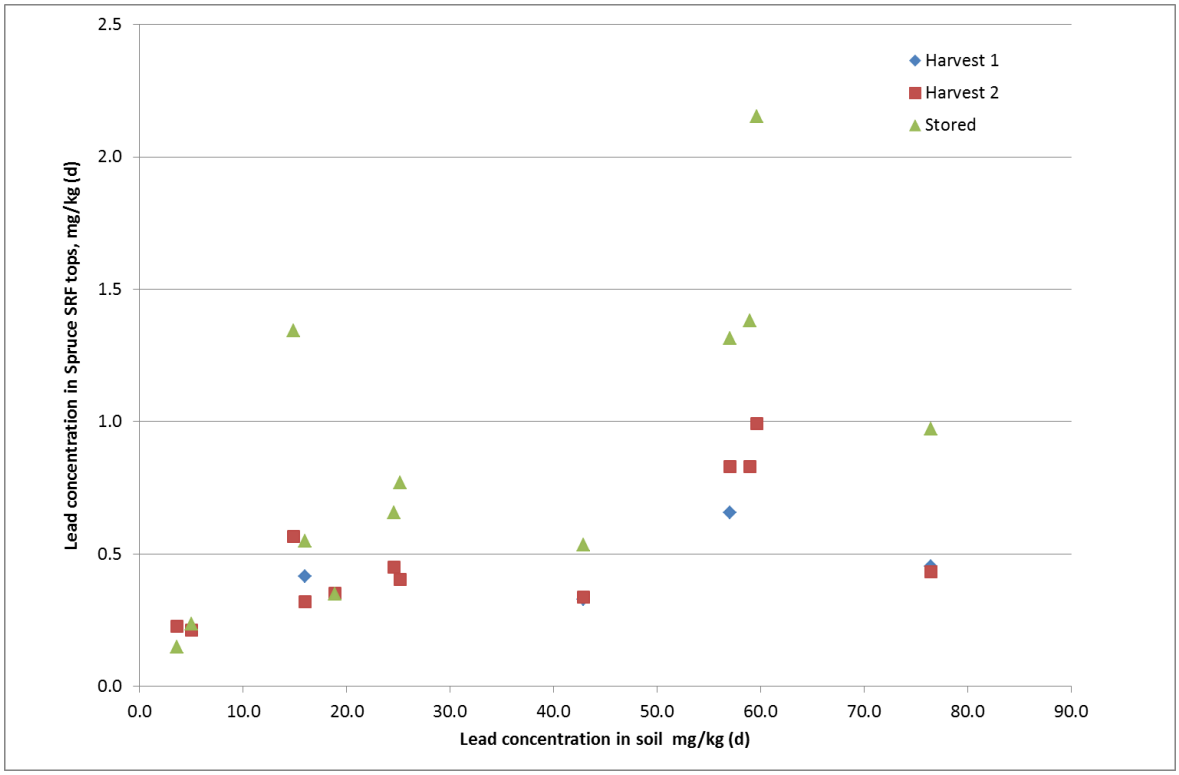


Figure 9-9: Correlation of lead in soil and feedstock for spruce SRF



.

Table 9-5: Structured factor analysis of spruce SRF tops

Variable	CZ	ST	HT	STORE	CZ & ST	CZ & HT	ST & HT	CZ & STORE	ST & STORE	HT & STORE	CZ & HT & ST	CZ & ST & STORE	CZ & HT & STORE	ST & HT & STORE	CZ & ST & HT & STORE
Moisture (ar)	0.810	0.618	0.000	0.000	0.189	0.023	0.967	0.507	0.876	0.002	0.406	0.323	0.269	0.881	0.084
Net calorific value (ar)	0.884	0.651	0.000	0.000	0.205	0.021	0.955	0.511	0.893	0.002	0.396	0.290	0.253	0.865	0.076
Ash content (d)	0.201	0.504	0.517	0.000	0.589	0.159	0.941	0.101	0.489	0.517	0.008	0.678	0.694	0.617	0.091
Volatile matter (DAF)	0.269	0.634	0.037	0.117	0.343	0.630	0.217	0.167	0.476	0.416	0.703	0.381	0.284	0.940	0.023
Gross calorific value (DAF)	0.452	0.076	0.012	0.188	0.266	0.285	0.766	0.506	0.252	0.001	0.287	0.864	0.802	0.642	0.421
Carbon (DAF)	0.817	0.463	0.112	0.001	0.602	0.890	0.945	0.142	0.738	0.133	0.315	0.603	0.763	0.714	0.488
Hydrogen (DAF)	0.128	0.154	0.075	0.000	0.654	0.293	0.891	0.552	0.653	0.001	0.126	0.936	0.664	0.688	0.930
Nitrogen (DAF)	0.086	0.720	0.480	0.000	0.451	0.682	0.871	0.083	0.742	0.101	0.081	0.754	0.838	0.423	0.836
Sulphur (DAF)	0.151	0.468	0.001	0.648	0.180	0.879	0.679	0.446	0.509	0.000	0.027	0.669	0.286	0.928	0.039
Chlorine (DAF)	0.147	0.120	0.066	0.000	0.934	0.323	0.387	0.561	0.981	0.106	0.331	0.220	0.193	0.142	0.233
Barium (d)	0.684	0.829	0.000	0.001	0.354	0.031	0.722	0.391	0.872	*	0.122	0.763	*	*	*
Chromium (d)	0.788	0.750	0.551	0.409	0.455	0.567	0.547	0.148	0.602	*	0.658	0.404	*	*	*
Cobalt (d)	0.347	0.438	0.410	0.008	0.568	0.906	0.769	0.838	0.318	*	0.417	0.461	*	*	*
Copper (d)	0.070	0.910	0.000	0.000	0.776	0.490	0.154	0.131	0.956	*	0.549	0.088	*	*	*
Molybdenum (d)	0.408	0.560	0.010	0.000	0.439	0.235	0.996	0.087	0.916	*	0.239	0.317	*	*	*
Nickel (d)	0.694	0.191	0.000	0.882	0.083	0.295	0.090	0.090	0.211	*	0.103	0.260	*	*	*
Vanadium (d)	0.656	0.346	0.023	0.006	0.792	0.574	0.521	0.582	0.801	*	0.591	0.192	*	*	*
Zinc (d)	0.212	0.898	0.003	0.854	0.401	0.580	0.424	0.430	0.920	*	0.051	0.840	*	*	*
Cadmium (d)	0.370	0.161	0.217	0.068	0.984	0.891	0.569	0.681	*	*	0.187	*	*	*	*
Lead (d)	0.427	0.571	0.002	0.011	0.482	0.815	0.572	0.279	*	*	0.323	*	*	*	*
Al_2O_3 (na)	0.217	0.968	0.745	0.000	0.036	0.625	0.492	0.966	0.752	*	0.137	0.083	*	*	*
BaO (na)	0.768	0.570	0.002	0.000	0.111	0.744	0.583	0.043	0.178	*	0.233	0.005	*	*	*
$CaCO_3$ (na)	0.212	0.720	0.012	0.000	0.229	0.085	0.887	0.310	0.749	*	0.621	0.014	*	*	*
Fe_2O_3 (na)	0.292	0.405	0.301	0.003	0.885	0.244	0.458	0.450	0.768	*	0.251	0.346	*	*	*
K_2O (na)	0.337	0.388	0.786	0.000	0.643	0.940	0.759	0.472	0.916	*	0.405	0.600	*	*	*
MgO (na)	0.606	0.866	0.009	0.965	0.393	0.986	0.860	0.773	0.833	*	0.582	0.827	*	*	*
Mn_3O_4 (na)	0.908	0.895	0.328	0.995	0.744	0.232	0.590	0.632	0.945	*	0.412	0.893	*	*	*

Variable	CZ	ST	HT	STORE	CZ & ST	CZ & HT	ST & HT	CZ & STORE	ST & STORE	HT & STORE	CZ & HT & ST	CZ & ST & STORE	CZ & HT & STORE	ST & HT & STORE	CZ & ST & HT & STORE
Na_2O (na)	0.411	0.708	0.001	0.051	0.581	0.538	0.633	0.059	0.714	*	0.254	0.816	*	*	*
P_2O_5 (na)	0.431	0.368	0.006	0.900	0.264	0.701	0.777	0.712	0.941	*	0.478	0.304	*	*	*
SiO_2 (na)	0.904	0.465	0.013	0.000	0.423	0.134	0.282	0.037	0.698	*	0.968	0.004	*	*	*
TiO_2 (na)	0.744	0.753	0.480	0.000	0.708	0.957	0.358	0.074	0.946	*	0.027	0.510	*	*	*
Aluminium (d)	0.489	0.843	0.858	0.009	0.012	0.163	0.269	0.506	0.128	*	0.651	0.002	*	*	*
Calcium (d)	0.013	0.677	0.138	0.007	0.703	0.915	0.890	0.305	0.325	*	0.015	0.724	*	*	*
Iron (d)	0.554	0.497	0.471	0.489	0.657	0.056	0.340	0.556	0.999	*	0.585	0.110	*	*	*
Potassium (d)	0.489	0.696	0.579	0.000	0.979	0.683	0.845	0.192	0.657	*	0.145	0.954	*	*	*
Magnesium (d)	0.465	0.999	0.074	0.001	0.074	0.600	0.861	0.313	0.703	*	0.361	0.598	*	*	*
Manganese (d)	0.877	0.832	0.583	0.062	0.702	0.140	0.554	0.435	0.938	*	0.161	0.504	*	*	*
Sodium (d)	0.144	0.600	0.003	0.174	0.556	0.646	0.545	0.565	0.266	*	0.585	0.428	*	*	*
Phosphorous (d)	0.787	0.856	0.066	0.184	0.384	0.391	0.681	0.993	0.853	*	0.981	0.114	*	*	*
Silicon (d)	0.436	0.504	0.022	0.000	0.670	0.014	0.860	0.017	0.966	*	0.290	0.007	*	*	*
Titanium (d)	0.945	0.824	0.225	0.000	0.575	0.632	0.313	0.091	0.970	*	0.066	0.318	*	*	*
Alkali index	0.356	0.578	0.573	0.000	0.895	0.727	0.866	0.213	0.644	*	0.167	0.919	*	*	*

†basis of analysis; ar = as received fuel, d = dry fuel, DAF = dry, ash-free fuel, na= normalised ash. * Indicates not included in structured analysis. Antimony, arsenic, mercury and bromine were not included in the structured analysis due to limits of detection. Dark blue cells indicate $p<0.001$; light blue cells $0.001<p<0.05$

Table 9-6: Mean values and assessment of relevance for interactions identified by structured analysis for spruce SRF tops (number of analyses if not default)

One factor analysis			
Parameter	Storage		Assessment
	Fresh	Stored	
Default number of analyses	24	12	
Ash, %wt (d)	2.4	2.0 (24)	Relevant for further study
Carbon, %wt (DAF)	53.63	54.08 (24)	Unlikely to have operational impact
Nitrogen, %wt (DAF)	0.93	0.76 (24)	Relevant for further study
Chlorine, % wt (DAF)	0.05	0.03 (24)	Relevant for further study
Ba, mg/kg (d)	36.03	30.72	Unlikely to have operational impact
Co, mg/kg (d)	0.12	0.10	Limit of detection level
Cu, mg/kg (d)	3.85	4.80	Unlikely to have operational impact
Mo, mg/kg (d)	0.12	0.10	Limit of detection level
V, mg/kg (d)	0.22	0.28	Unlikely to have operational impact
Pb, mg/kg (d)	0.488 (16)	0.867	Relevant for further study
Al_2O_3, %wt (na)	1.13	1.55	Unlikely to have operational impact
$CaCO_3$, %wt (na)	45.41	51.98	Relevant for further study
Fe_2O_3, %wt (na)	0.52	0.68	Unlikely to have operational impact
K_2O, %wt (na)	19.82	15.29	Relevant for further study
SiO_2, %wt (na)	11.20	8.70	Relevant for further study
TiO_2, %wt (na)	0.04	0.09	Unlikely to have operational impact
Al, mg/kg (d)	116	135	Unlikely to have operational impact
Ca, mg/kg (d)	3594	3362	Relevant for further study
K, mg/kg (d)	3288	2053	Relevant for further study
Mg, mg/kg (d)	896	780	Unlikely to have operational impact
Si, mg/kg (d)	1127	703	Relevant for further study
Ti, mg/kg (d)	4.5	8.4	Unlikely to have operational impact
Alkali Index	0.194	0.125	Relevant for further study
	Harvest Time		
	1	2	
Default number of analyses	24	12	
Volatile Matter, %wt (DAF)	78.6	78.2 (24)	Analytical repeatability
Cu, mg/kg (d)	4.39	3.73	Unlikely to have operational impact
Mo, mg/kg (d)	0.11	0.12	Limit of detection level
Ni, mg/kg (d)	0.74	0.65	Unlikely to have operational impact
V, mg/kg (d)	0.25	0.21	Unlikely to have operational impact
Zn, mg/kg (d)	34.05	30.66	Unlikely to have operational impact
Pb, mg/kg (d)	0.766 (16)	0.496	Relevant for further study
BaO, wt% (d)	0.23	0.17	Unlikely to have operational impact
$CaCO_3$, wt% (d)	48.62	45.58	Relevant for further study
MgO, wt% (d)	8.00	7.19	Relevant for further study
Na_2O, wt% (d)	0.97 (23)	0.74	Relevant for further study
P_2O_5, wt% (d)	9.56 (23)	11.13	Relevant for further study
SiO_2, wt% (d)	9.95	11.19	Relevant for further study
Na, mg/kg (d)	137.2	101.2	Relevant for further study

Two factor analysis				
Parameter	Harvest Time / Storage	1	2	Assessment
Default number of analyses		12	12	
Moisture, %wt (ar)	Fresh	54.2	57.7	Relevant for further study
	Stored	37.7	50.3	
NCV, kJ/kg (ar)	Fresh	7852	6944	Relevant for further study
	Stored	11472	8680	
GCV, kJ/kg (DAF)	Fresh	21914	21602	Repeatability of analysis
	Stored	21666	21710	
H, %wt (DAF)	Fresh	6.50	6.42	Unlikely to have operational impact
	Stored	6.32	6.34	
Sulphur, %wt (DAF)	Fresh	0.03	0.05	Relevant for further study
	Stored	0.04	0.04	
	Climate zone / Storage	Cold/wet	Warm/ moist	
Default number of analyses	Fresh	12	12	
	Stored	6	6	
BaO, %wt (na)	Fresh	0.19	0.15	Unlikely to have operational impact
	Stored	0.28	0.31	
Si, mg/kg (d)	Fresh	921.2	1332.5	Relevant for further study
	Stored	778.8	627	
	Climate zone / Soil Type	Cold/wet	Warm/ moist	
Al_2O_3, %wt (na)	Mineral	* (0)	1.20 (6)	Relevant for further study
	Organic	1.98 (3)	0.87 (6)	
	Peat	1.29 (15)	1.34 (6)	
	Climate zone / Harvest time	Cold/wet	Warm/ moist	
Default number of analyses		12	12	
Moisture, %wt (ar)	1	47.8	44.1	Relevant for further study
	2	52.6	55.3	
NCV, kJ/kg (ar)	1	9276	10048	Relevant for further study
	2	8129	7495	
Ba, mg/kg (d)	1	39.6	32.4	Unlikely to have operational impact
	2	31.1 (6)	30.34 (6)	
Si, mg/kg (d)	1	879	962	Relevant for further study
	2	864 (6)	1368 (6)	

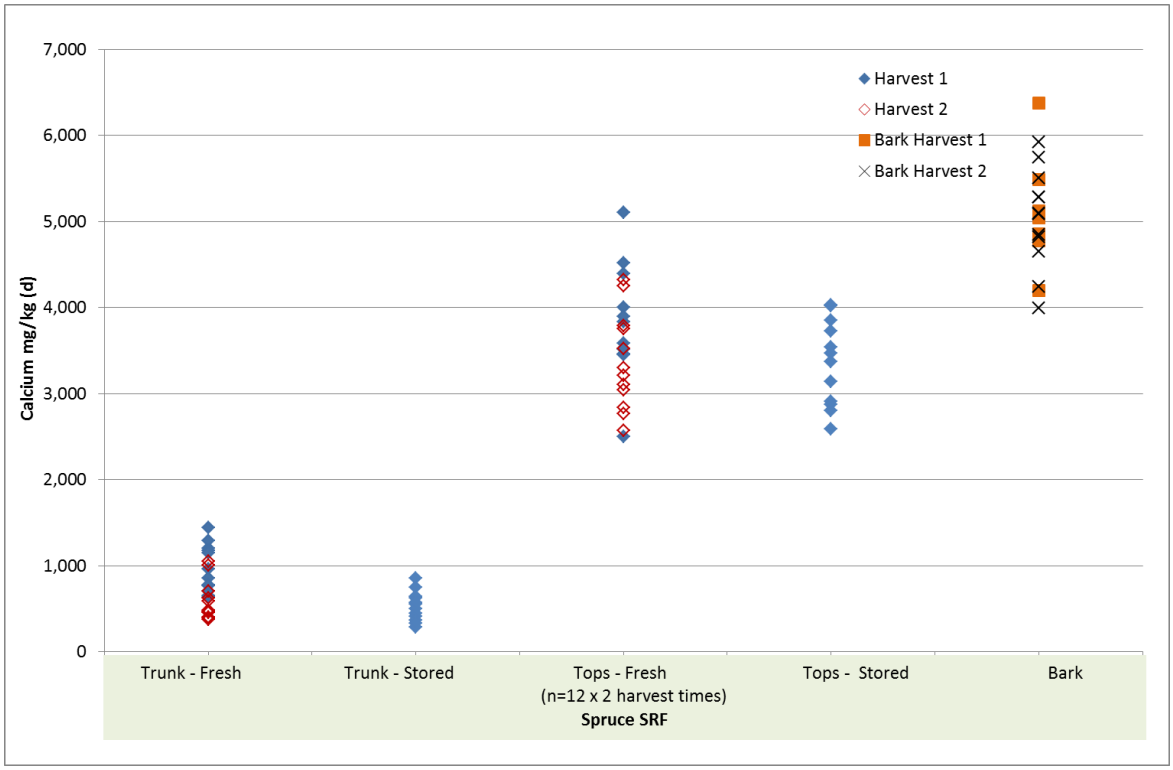
Table 9-7: Mean values and assessment of relevance for interactions identified by structured analysis for spruce SRF tops cont. (number of analyses if not default)

Three factor analysis								
Parameter	Climate zone	Cold/wet			Warm/moist			Assessment
	Soil Type / Storage	Mineral	Organic	Peat	Mineral	Organic	Peat	
Default number of analyses	Fresh	0	2	10	4	4	4	
	Stored	0	1	5	2	2	2	
BaO, %wt (na)	Fresh	*	0.16	0.20	0.11	0.23	0.12	Unlikely to have operational impact
	Stored	*	0.20	0.29	0.19	0.53	0.20	
$CaCO_3$, %wt (na)	Fresh	*	42.16	45.38	43.73	46.72	47.51	Unlikely to have operational impact
	Stored	*	44.17	50.34	52.41	59.72	51.84	
SiO_2, %wt (na)	Fresh	*	15.53	9.72	11.34 (3)	14.07	9.74	Unlikely to have operational impact
	Stored	*	16.53	8.17	10.28	6.03	7.18	
Al, mg/kg (d)	Fresh	*	165	110.6	111.4	88.2	136.6	Unlikely to have operational impact
	Stored	*	299.7	119.7	135.9	100.9	126.1	
Si, mg/kg (d)	Fresh	*	1365	832	1521	1556	921	Unlikely to have operational impact
	Stored	*	1698	595	846	495	540	
	Soil Type / Harvest Time	Mineral	Organic	Peat	Mineral	Organic	Peat	
Default number of analyses		0	2	10	4	4	4	
Ash, wt% (d)	1	*	2.7	1.9	2.4	2.2	2.2	Relevant for further study
	2	*	2.3	2.0	2.6	2.5	2.0	
Sulphur, wt% (DAF)	1	*	0.05	0.03	0.04	0.03	0.04	Relevant for further study
	2	*	0.05	0.04	0.05	0.06	0.04	
Ca, mg/kg (d)	1	*	3683	3247	3722	3948	3902	Unlikely to have operational impact
	2	*	2836 (1)	3138 (5)	3525 (2)	4287 (2)	3158 (2)	
TiO_2, %wt (na)	1	*	0.04	0.06	0.06	0.05	0.06	Unlikely to have operational impact
	2	*	0.06 (1)	0.06 (5)	0.04 (2)	0.03 (2)	0.11 (2)	

Four factor analysis														
Parameter	Climate zone	Cold/wet						Warm/moist						Assessment
	Soil type	Mineral		Organic		Peat		Mineral		Organic		Peat		
	Harvest time / Storage	1	2	1	2	1	2	1	2	1	2	1	2	
Default number of analyses		0	0	1	1	5	5	2	2	2	2	2	2	
Volatile matter, %wt (DAF)	Fresh	*	*	78.2	77.7	79.0	78.9	78.4	77.0	78.3	78.9	79.2	77.9	Unlikely to be operationally significant
	Stored	*	*	77.6	78.5	78.6	78.1	78.4	77.9	78.3	78.3	78.2	78.3	
Sulphur, %wt (DAF)	Fresh	*	*	0.03	0.06	0.02	0.05	0.04	0.06	0.03	0.06	0.04	0.05	
	Stored	*	*	0.07	0.04	0.03	0.03	0.04	0.04	0.04	0.06	0.05	0.04	Relevant for further review

The harvest time also appeared to have some impact on the concentration of the macroelements including the oxides of calcium, magnesium, sodium, phosphorous and silicon in ash. With the exception of phosphorous and silicon, concentrations generally decreased from the first to the second harvest, but many of the changes were small. Figure 9-10 illustrates the changes in calcium content. Despite this, the statistical analysis suggested that soil type had no impact on any characteristics of the tops, whilst for climate zone just one impact was highlighted, for calcium, which was judged to be operationally insignificant.

Figure 9-10: Results from the calcium analysis of spruce SRF (note – calcium in fuel is back calculated from ash oxide composition)



As for the trunk part (see Section 9.2.1), the six possible two-way combinations of the structured factors only illustrate a handful of impacts on the tops, the majority of these as a result of the interaction of harvest time & storage. Again, moisture and NCV were impacted, with harvest 2 containing more moisture (see Figure 9-2 and Figure 9-3), but DAF sulphur was also affected, being higher in the second harvest. A similar observation was made for the poplar SRF tops (see Section 8.2.2).

The combination of climate zone and harvest time is also seen to have an impact on moisture content and NCV, although the differences were relatively small and possibly linked to the weather conditions at the time of harvest. Silicon levels in the fuel were also higher in the second harvest from the warm/moist climate zone condition. The combination of climate zone and soil type appeared to affect Al_2O_3 in ash concentrations, but the limited number of samples in some of the datasets makes interpretation difficult.

The combinations of soil type & month and soil type & storage had no impact on any characteristics.

Of the three-way and four-way interactions, the impact on DAF sulphur and dry ash was judged to be of interest from the combination of climate zone & soil type & harvest time. Although the number of datasets for each combination is low, the sulphur and ash levels appear to track each other to some extent. However, all of the other impacts identified were considered operationally insignificant.

9.2.3 Bark

For the spruce SRF bark, the samples were only taken for the freshly harvested material and storage was not considered. As shown in Table 9-8, the statistics highlighted harvest time as the factor influencing most feedstock characteristics, with soil type and climate zone affecting just a handful. Harvest time affected NCV with the second harvest on average lower in energy content; inspection of Figure 9-3 however reveals that just a couple of samples appear to be responsible for this change. Interestingly, although the moisture content of second harvest was, on average, higher by nearly 2%, the statistics did not highlight this as a significant impact, nevertheless this is the underlying reason for the change in NCV. Figure 9-2 illustrates that, once again just a couple of high moisture content samples have caused the average to shift. It was judged that there were insufficient grounds to reject these high readings from the analysis as outliers as they could be the result of surface wetness due to the conditions at the time of sample collection rather than inherent moisture content of the bark. The dry nitrogen content was also approximately 0.1% lower in the second harvest as shown in Figure 9-7. Although the statistics highlighted many other trace elements and macroelements as being impacted by harvest time, as shown in Table 9-9, the only one considered worthy of highlighting was phosphorous (as P_2O_5 in ash and also as phosphorous in the fuel), which reduced slightly in the second harvest, as shown in Figure 9-11.

Figure 9-11: Results from the phosphorous analysis of spruce SRF (note – phosphorous in fuel is back calculated from ash oxide composition)

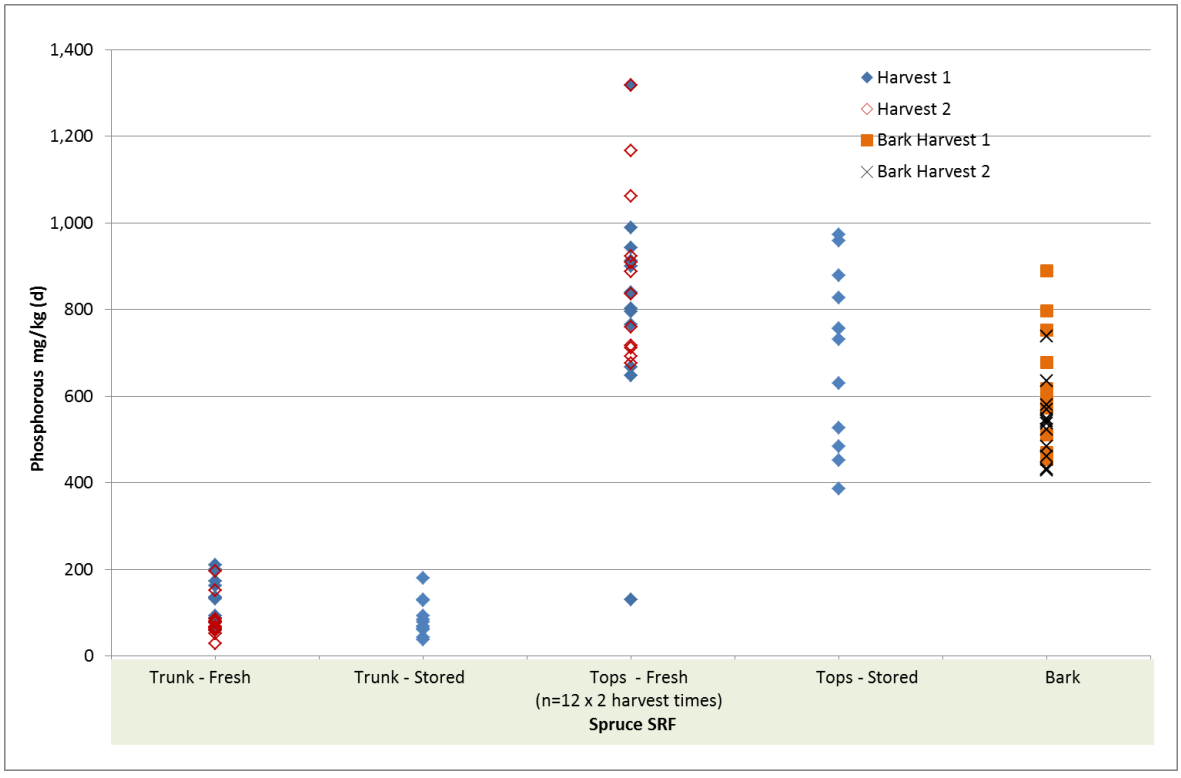


Table 9-8: Structured factor analysis of spruce SRF bark

Variable	CZ	ST	HT	CZ & ST	CZ & HT	ST & HT	CZ & ST & HT
Moisture (ar)	0.778	0.619	0.119	0.490	0.248	0.918	0.319
Net calorific value (ar)	0.972	0.602	0.028	0.608	0.250	0.935	0.252
Ash content (d)	0.087	0.316	0.052	0.379	0.567	0.916	0.894
Volatile matter (DAF)	0.605	0.804	0.521	0.284	0.766	0.901	0.616
Gross calorific value (DAF)	0.139	0.524	0.000	0.595	0.950	0.940	0.500
Carbon (DAF)	0.445	0.420	0.512	0.863	0.528	0.720	0.850
Hydrogen (DAF)	0.416	0.722	0.010	0.995	0.791	0.794	0.962
Nitrogen (DAF)	0.085	0.647	0.003	0.849	0.683	0.472	0.727
Chlorine (DAF)	0.121	0.824	0.024	0.792	0.802	0.453	0.483
Barium (d)	0.575	0.858	0.785	0.612	0.035	0.806	0.980
Chromium (d)	0.439	0.365	0.885	0.274	0.717	0.681	0.565
Cobalt (d)	0.156	0.390	0.001	0.651	0.445	0.636	0.137
Copper (d)	0.129	0.901	0.001	0.913	0.708	0.320	0.008
Molybdenum (d)	0.156	0.390	0.001	0.651	0.445	0.636	0.137
Nickel (d)	0.410	0.312	0.769	0.571	0.214	0.795	0.296
Vanadium (d)	0.646	0.432	0.011	0.694	0.762	0.626	0.681
Zinc (d)	0.068	0.964	0.765	0.804	0.154	0.969	0.370
Cadmium (d)	0.767	0.948	0.531	0.704	0.333	0.928	*
Lead (d)	0.806	0.524	0.527	0.715	0.327	0.458	*
Al_2O_3 (na)	0.846	0.810	0.414	0.087	0.232	0.314	0.030
BaO (na)	0.483	0.803	0.010	0.716	0.006	0.859	0.190
$CaCO_3$ (na)	0.125	0.824	0.000	0.688	0.939	0.265	0.841
Fe_2O_3 (na)	0.936	0.448	0.081	0.726	0.399	0.368	0.833
K_2O (na)	0.045	0.633	0.196	0.140	0.963	0.841	0.764
MgO (na)	0.798	0.752	0.095	0.707	0.495	0.889	0.990
Mn_3O_4 (na)	0.385	0.893	0.672	0.942	0.294	0.311	0.212
Na_2O (na)	0.040	0.444	0.001	0.761	0.510	0.320	0.792
P_2O_5 (na)	0.871	0.045	0.003	0.200	0.585	0.368	0.322
SiO_2 (na)	0.216	0.887	0.059	0.678	0.822	0.115	0.871
TiO_2 (na)	0.127	0.884	0.938	0.641	0.698	0.762	0.042
Aluminium (d)	0.565	0.880	0.098	0.113	0.108	0.290	0.012
Calcium (d)	0.042	0.238	0.912	0.772	0.738	0.673	0.753
Iron (d)	0.801	0.512	0.007	0.674	0.338	0.389	0.924
Potassium (d)	0.353	0.474	0.130	0.334	0.941	0.840	0.767
Magnesium (d)	0.514	0.939	0.001	0.705	0.529	0.935	0.686
Manganese (d)	0.412	0.967	0.988	0.916	0.348	0.297	0.218
Sodium (d)	0.014	0.220	0.000	0.842	0.756	0.315	0.970
Phosphorous (d)	0.766	0.332	0.000	0.325	0.582	0.557	0.524
Silicon (d)	0.150	0.802	0.007	0.606	0.587	0.133	0.977
Titanium (d)	0.115	0.883	0.929	0.625	0.838	0.669	0.024
Alkali index	0.539	0.401	0.148	0.333	0.908	0.830	0.755

†basis of analysis; ar = as received fuel, d = dry fuel, DAF = dry, ash-free fuel, na= normalised ash. * Indicates not included in structured analysis. Antimony, arsenic, mercury, sulphur and bromine were not included in the structured analysis due to limits of detection. Dark blue cells indicate $p<0.001$; light blue cells $0.001<p<0.05$

Table 9-9: Mean values and assessment of relevance for interactions identified by structured analysis for spruce SRF bark (number of analyses if not default)

One factor analysis			
Parameter	Harvest Time		Assessment
	1	2	
Default number of analyses	12	12	
NCV, kJ/kg (ar)	7030	6514	Relevant for further study
GCV, kJ/kg (DAF)	21601	21183	Within analytical repeatability
H, %wt (DAF)	6.15	6.04	Within analytical repeatability
N, %wt (DAF)	0.63	0.54	Relevant for further study
Chlorine, % wt (DAF)	0.04	0.03	Within analytical repeatability
Co, mg/kg (d)	0.13	0.12	Limit of detection levels
Cu, mg/kg (d)	4.61	4.09	Unlikely to have operational impact
Mo, mg/kg (d)	0.13	0.12	Limit of detection levels
V, mg/kg (d)	0.35	0.28	Unlikely to have operational impact
BaO, %wt (na)	0.67	0.72	Unlikely to have operational impact
$CaCO_3$, %wt (na)	61.68	65.05	Unlikely to have operational impact
Na_2O, %wt (na)	0.85	0.70	Unlikely to have operational impact
P_2O_5, %wt (na)	7.10	6.37	Relevant for further study
Fe, mg/kg (d)	58.9	48.3	Unlikely to have operational impact
Mg, mg/kg (d)	758	669	Unlikely to have operational impact
Na, mg/kg (d)	130.6	101.5	Unlikely to have operational impact
P, mg/kg (d)	640.7	540.1	Relevant for further study
Si, mg/kg (d)	313.2	244.4	Unlikely to have operational impact
	Climate zone		
	Cold/wet	Warm/ moist	
Default number of analyses	12	12	
K_2O, %wt (na)	16.44	14.73	Unlikely to have operational impact
Na_2O, %wt (na)	0.85	0.70	Relevant for further study
Ca, mg/kg (d)	4833	5266	Unlikely to have operational impact
Na, mg/kg (d)	92.1	140	Relevant for further study
	Soil Type		
	Mineral	Organic	Peat
Default number of analyses	4	6	14
P_2O_5, %wt (na)	5.14	6.59	7.252
Two factor analysis			
Parameter	Climate zone / Harvest time	Cold/ wet	Warm/ moist
Default number of analyses		6	6
Ba, mg/kg (d)	1	148.9	114.6
	2	139.1	127.3
BaO, %wt (na)	1	0.76	0.57
	2	0.76	0.67

Table 9-10 Mean values and assessment of relevance for interactions identified by structured analysis for spruce SRF bark cont. (number of analyses if not default)

Three factor analysis								
	Climate zone	Cold/wet			Warm/moist			Assessment
	Soil Type / Harvest time	Mineral	Organic	Peat	Mineral	Organic	Peat	
Default number of analyses		0	1	5	2	2	2	
Cu, mg/kg (d)	1	*	3.35	4.31	4.69	5.40	5.12	Unlikely to have operational impact
	2	*	4.60	3.51	4.18	4.72	4.56	
Al_2O_3, %wt (na)	1	*	0.89	0.94	1.11	1.00	1.14	Relevant for further study
	2	*	1.89	0.78	0.79	0.86	0.98	
TiO_2, %wt (na)	1	*	0.01	0.03	0.07	0.08	0.02	Unlikely to have operational impact
	2	*	0.05	0.03	0.05	0.05	0.06	
Al, mg/kg (d)	1	*	95.4	97.4	132.0	109.2	124.1	Relevant for further study
	2	*	188.9	78.1	88.9	84.0	103.4	
Ti, mg/kg (d)	1	*	1.4	3.6	8.4	9.1	2.3	Unlikely to have operational impact
	2	*	5.5	3.2	6.2	5.7	7.4	

Climate zone influenced four characteristics, but only the effects on Na_2O in ash and sodium in the fuel were judged to be of interest – showing an increase in the warm/moist climate zone. Soil type only impacted on one characteristic – P_2O_5 in ash with the lowest concentrations in mineral soils increasing to the highest concentration in peat soils. No correlation was seen between phosphorous content of the soil and the phosphorous levels in the spruce SRF feedstocks.

Of the interactions of two structured factors, only the combination of climate zone & harvest time had any impact on feedstock characteristics (on BaO in ash and barium in the fuel) both of which were judged to be operationally insignificant.

The three-way interaction of the structured factors impacted on a total of five characteristics; of these only the impact on Al_2O_3 in ash and aluminium in fuel was judged to be operationally significant, as shown in Table 9-10. Generally the concentration of aluminium tended to decrease in the second harvest, but interpreting the data from each soil type and climate zone was difficult given the low number of data points for each condition.

9.3 Null hypothesis

Of the many site properties collected for spruce SRF, the following had sufficient variation in the data to be suitable for statistical analysis: planting density, soil classification, age of sampled material, pH and cation exchange capacity (CEC). In this section, planting density, which ranged from ca. 750 to 2800 stems per hectare, and age of the sampled material, which ranged from 11 to 16 years old, are considered by correlation analysis (as discussed in Section 2.6.3). The impact of soil classification was investigated in Section 9.2, and the impact of pH and CEC are covered in the correlation analysis, which is discussed in Section 9.4.

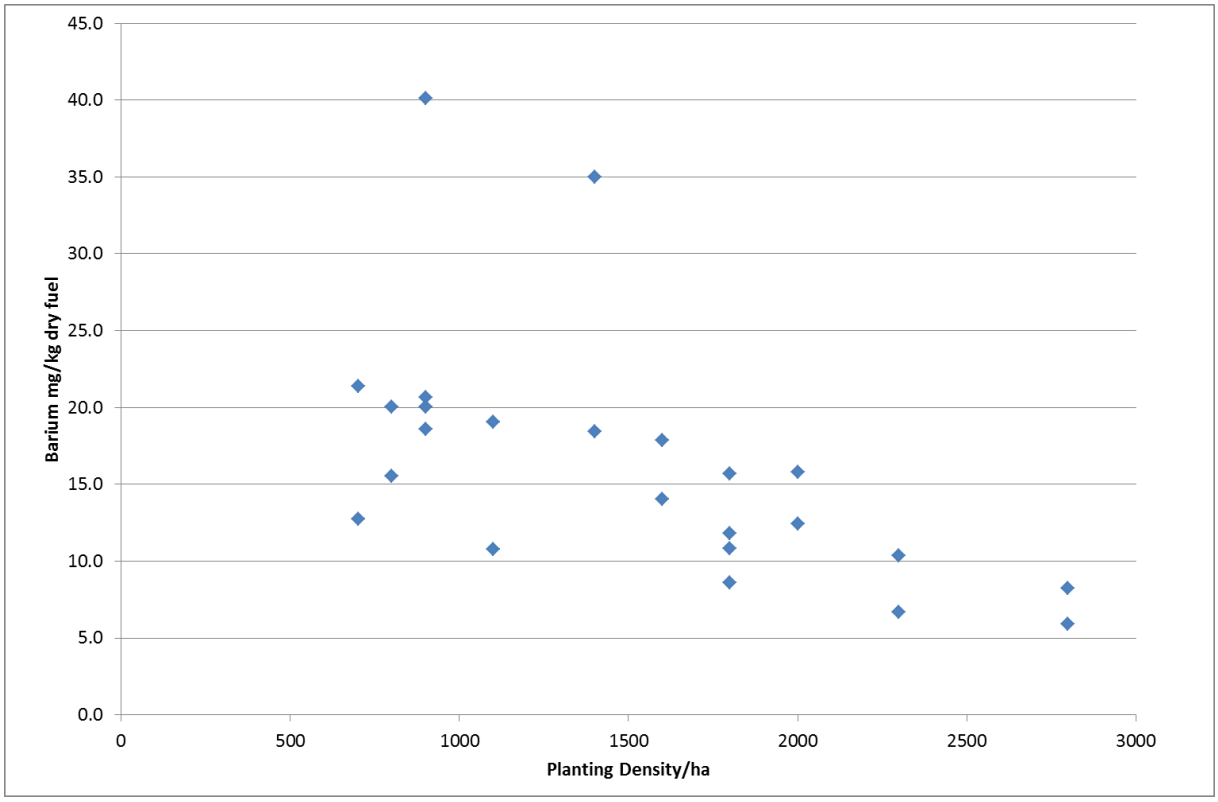
The full results of the correlation analysis are presented in Appendix 5, with these tables colour-coded to indicate those correlations (positive or negative) which explain either >50% or >80% of the variability, as discussed in Section 2.6.5. Table 9-11 presents an extract of this table, showing the strongest correlations.

Table 9-11: Regressions between selected provenance information and feedstock characteristics of fresh spruce SRF

	Trunk wood		Tops		Bark	
Variable (basis)	**Planting density**	**Age of sampled stems**	**Planting density**	**Age of sampled stems**	**Planting density**	**Age of sampled stems**
Ash content (d)	-0.221	-0.140	0.625	0.803	0.663	0.647
Volatile matter (DAF)	0.085	0.062	-0.736	-0.631	-0.472	-0.455
Nitrogen (DAF)	-0.087	0.009	0.718	0.715	0.008	0.180
Barium (d)	-0.712	-0.495	-0.417	-0.032	-0.304	-0.064
Cobalt (d)	-0.348	-0.128	0.524	0.729	0.593	0.613
Copper (d)	-0.517	-0.414	0.727	0.581	0.525	0.284
Molybdenum (d)	-0.399	-0.285	0.611	0.787	0.593	0.613
Arsenic (d)	0.207	-0.248	0.382	0.546	0.346	0.751
Mercury (d)	-0.354	0.000	-0.120	0.440	0.742	0.351
Cadmium (d)	0.266	0.247	0.725	0.544	-0.131	-0.013

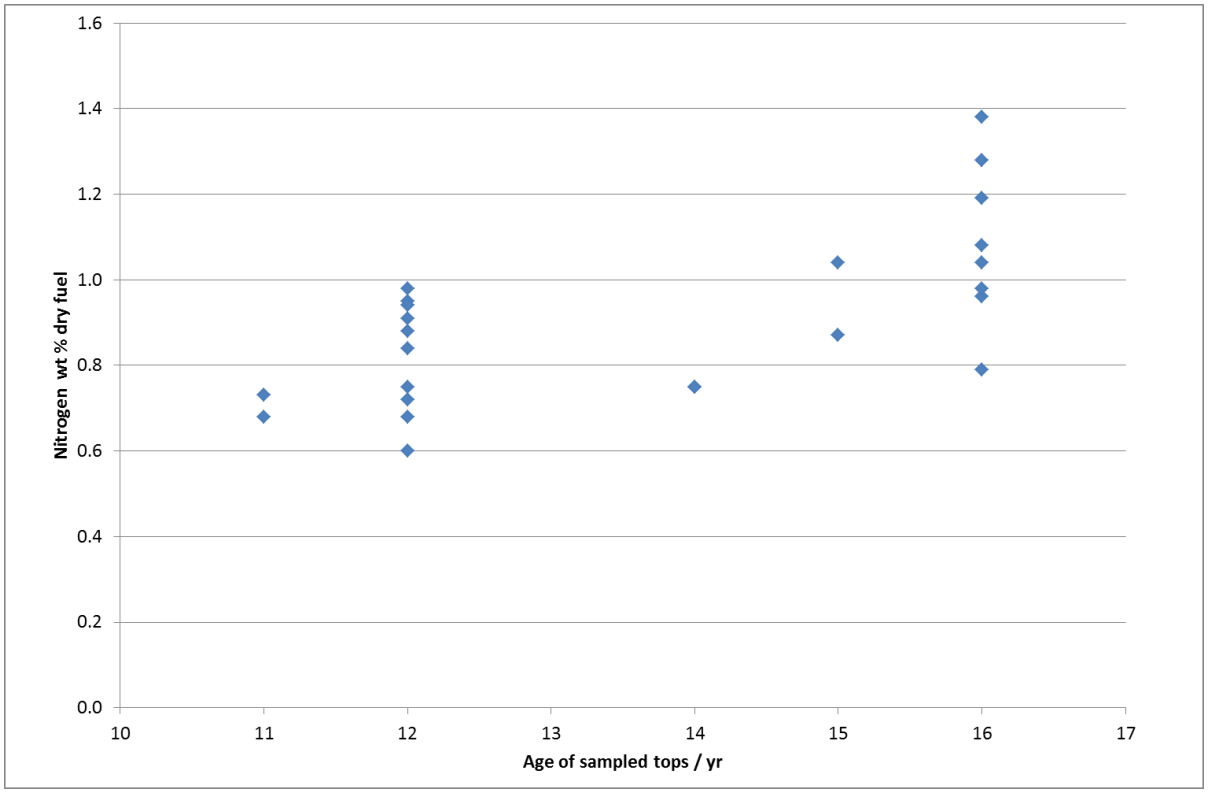
For the spruce SRF trunks, levels of barium were apparently negatively affected by planting density. although this is not of great operational significance for current conversion technologies (Figure 9-12). The age of the sampled material was not an important determinant for any of the feedstock characteristics (see Appendix 11).

Figure 9-12: Levels of barium in spruce SRF trunk samples (both harvests) compare to planting density



In the case of tops of spruce SRF, planting density was positively related to the following operationally important feedstock properties: nitrogen, copper and cadmium of which nitrogen and cadmium are of greatest practical significance. Planting density was negatively related to volatile matter. The other management factor, i.e. age of sampled stems, seemed to be closely related to ash content and nitrogen in the dry fuel (both increasing with the age of the samples) (Figure 9-13). While cobalt and manganese both showed positive correlations with the age of the sampled tops, these elements were present at limit of detection levels.

Figure 9-13: Correlation between nitrogen in the fuel and age of the sampled spruce SRF tops



Of the management factors investigated for their impact on bark characteristics, planting density was positively related to the mercury level while the age of sampled material was positively related to the arsenic concentrations. In both cases however this may be an artefact of the small data set (as not every sample was analysed for trace metals) and the limited range of values for planting density/age of material for which these elements were determined.

9.4 Determining factors

Determining the factors of greatest importance to feedstock characteristics can only be done in a qualitative way by review of the statistical analyses performed. For spruce SRF the structured factors were climate zone, soil type, harvest time and storage for the trunk and tops and climate zone, soil type, and harvest time for bark. The other statistical analyses to be considered are the correlations with soil characteristics and the correlations with site information (where these were possible).

The statistics for spruce SRF trunk (de-barked) highlighted many impacts of the four individual structured factors. Storage and harvest time had the most impact, with just two characteristics influenced by climate zone and none influenced by soil type. A limited number of impacts were also highlighted by the interactions of two of the factors, in particular the combination of harvest time and storage. Few significant impacts from combinations of three factors and all four factors were observed. Storage had a large impact on moisture content on the trunk material; NCV was also strongly influenced as a consequence. Storage also appears to affect the dry ash content and hence the levels of a number of macroelements to some extent, particularly from the first harvest, including aluminium, iron, potassium, phosphorous and silicon (and their respective oxides in ash), their concentrations tending to show a decrease on storage. Harvest time tended to influence levels of a number of macroelements, including sodium, silicon, calcium and potassium, which are lower in samples taken from the second harvest.

The tops of spruce SRF showed much the same pattern of influential factors, with storage and harvest time having the most impact, just one characteristic influenced by climate zone and none influenced by soil type (Table 9-5). A limited number of impacts were also highlighted by the interactions of two of the factors, in particular the combination of harvest time and storage. The number of significant impacts from combinations of three factors and finally the combination of all four factors were lower still. Storage impacted on the moisture content and consequently the net calorific value of the tops as well as dry ash content, DAF nitrogen and DAF chlorine. Of the other impacts, there were noteworthy changes in calcium and potassium, and their respective oxides in ash, and the trace element lead.

Harvest time had the greatest influence on bark characteristics, but only those for NCV and phosphorous (as P_2O_5 in ash and also as phosphorous in the fuel) were determined to be noteworthy. Soil type and climate zone affected just a handful of parameters of which only sodium/Na_2O (for climate zone), P_2O_5 (for soil type) and aluminium/Al_2O_3 (for the combination of all three factors) were significant.

As discussed in Section 2.6.3, the total variation explained by all of the factors: climate zone, soil type, harvest time, and storage was quantified using REML; the result of this (for all feedstocks) is presented in Appendix 9. Although this approach draws together only these four factors (as opposed to other factors such as soil composition and management factors), the total variation explained is a robust estimate of their power to explain the variation in feedstock characteristics. These factors explained 59% of the total variation in the moisture and net CV of the trunk wood and 44% of that in ash content. For the macroelements, 20-40% of the variation could be explained, with calcium and potassium at the top end of this range.

For the spruce SRF tops, 61% of the variation in moisture and net calorific value and 48% of the variation in ash content could be explained.

The explainable variation for both the spruce SRF trunk and tops was lower for the trace elements, macroelements and ash composition than for the major fuel parameters.

For the bark, the interactions of the structured factors explained 26% of the variation in net calorific value and 45% and 47% of the variation in phosphorus in the fuel and P_2O_5 in ash respectively.

Few relationships between soil properties and feedstock characteristics of spruce SRF were identified, with none for the spruce SRF trunk. For the tops:

- copper concentrations in crop were negatively related to the available zinc in the soil (Figure 9-14). Due to its toxicity, zinc (or any metal/metalloid) if present in the soil in high readily available levels could negatively influence plant uptake of other elements, some more than others; the impact on individual elements is likely to be influenced by soil pH. In light of the small number of data points, this particular relationship is noted but not considered in depth.
- there was a tendency for nitrogen concentrations in crop to be negatively related to the available magnesium in the soil (Figure 9-15).

Figure 9-14: Correlation between copper in the spruce SRF tops and available zinc in soil

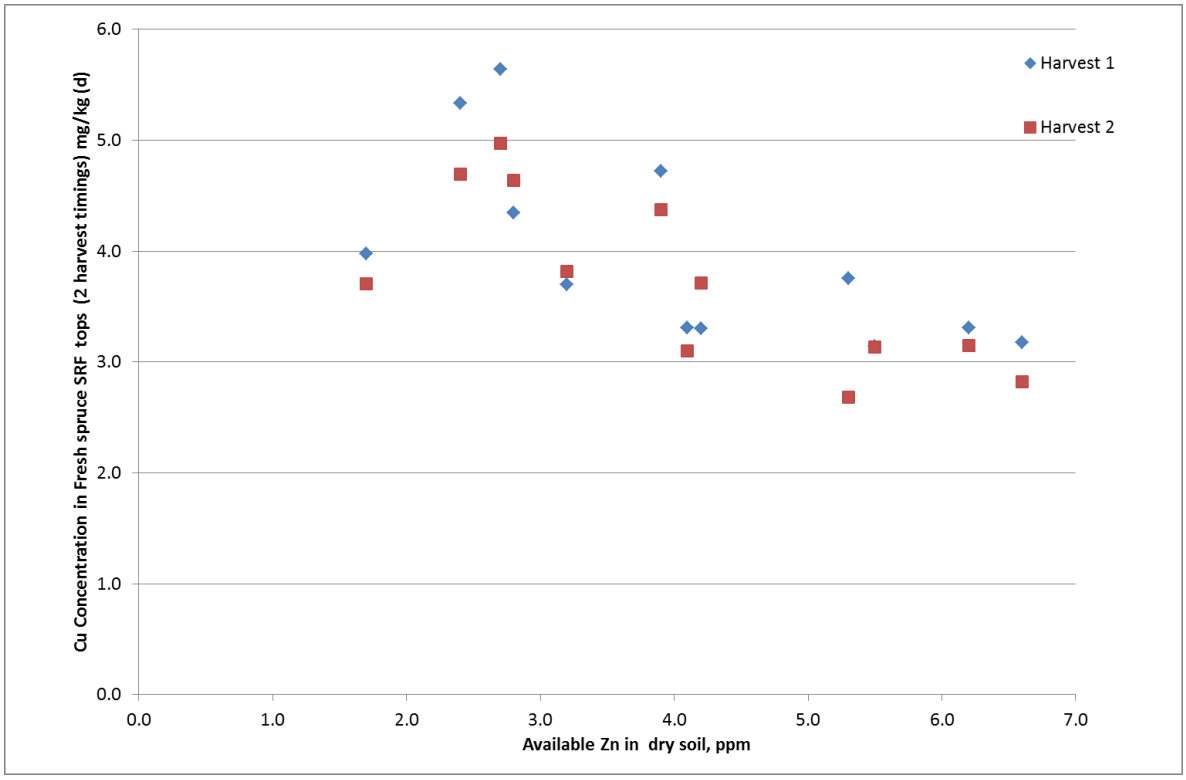
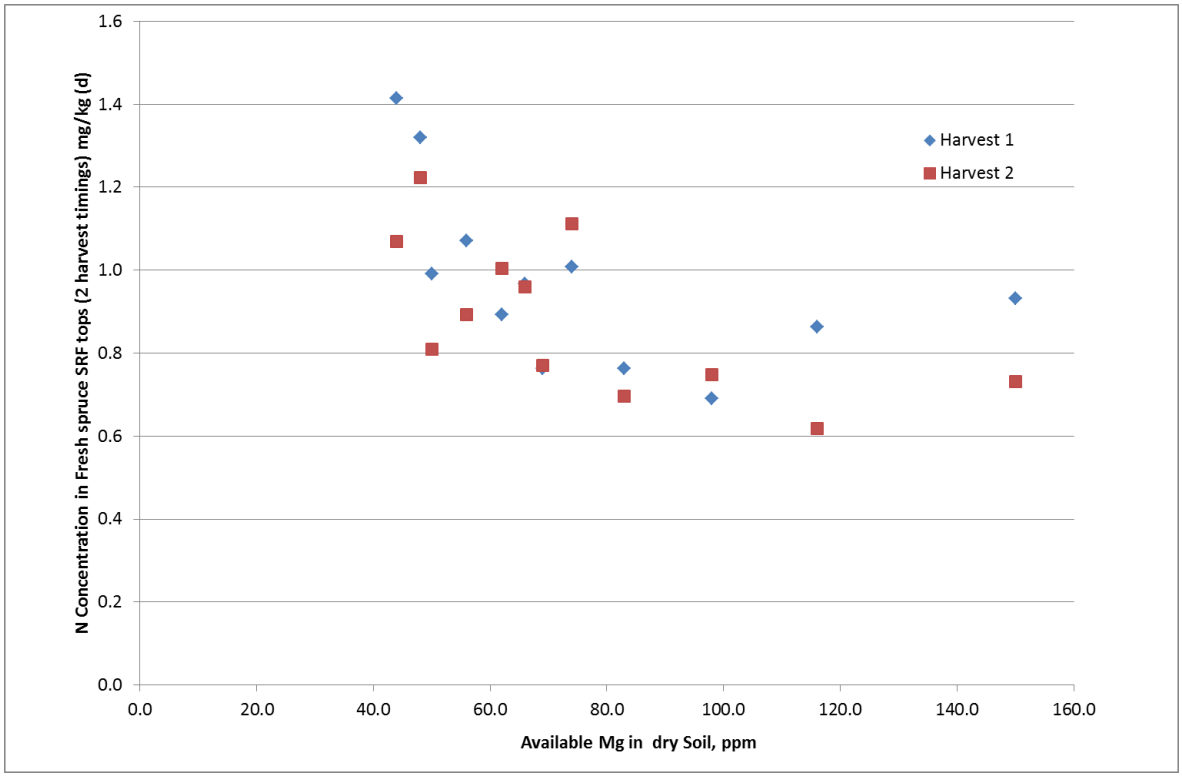


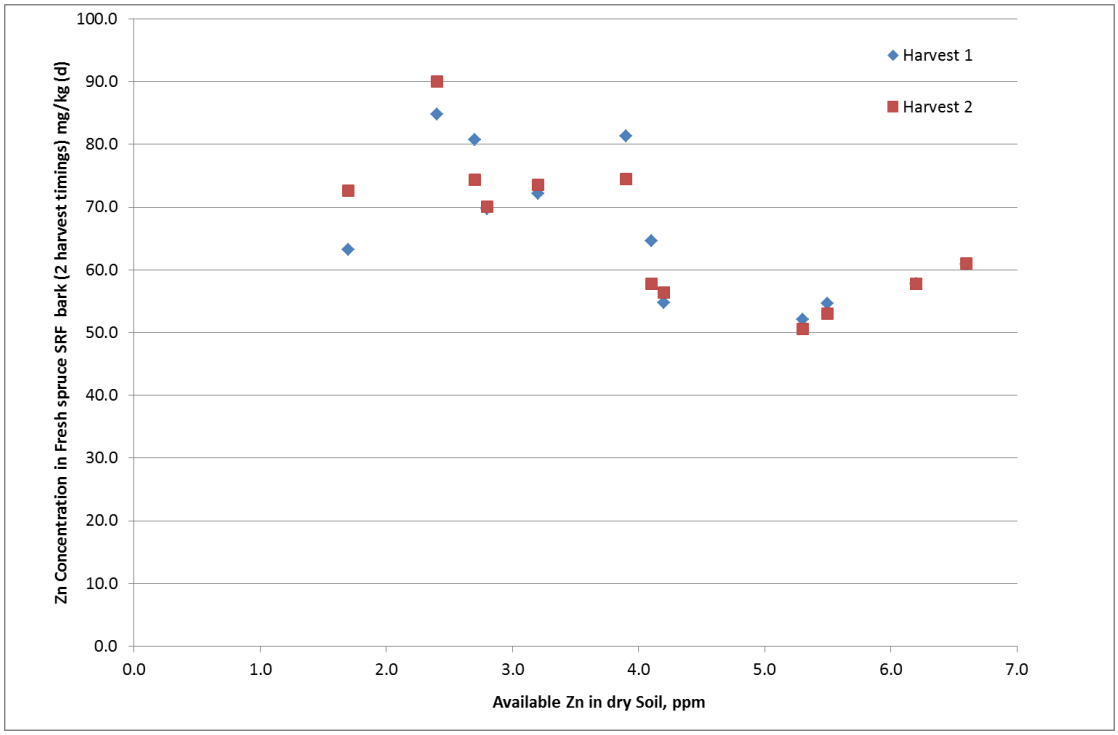
Figure 9-15: Correlation between nitrogen in spruce SRF tops with available magnesium in the soil



The principal observations for spruce SRF bark were:

- there was a tendency for both zinc and sodium in the crop to be negatively related to the available zinc in the soil (Figure 9-16).

Figure 9-16: Correlation between zinc in the spruce SRF bark and available zinc in the soil



Management factors, i.e. planting density and the age of the sampled material, were linked to a small number of feedstock properties. As planting density increased, the barium concentrations in the trunk wood fell, as did the volatile matter of the tops. Nitrogen, copper and cadmium of the tops increased with planting density. As the age of the sampled material increased, ash and nitrogen content of the tops increased.

As with the previous feedstocks, the various influences described above have been collated, focussed on the variables thought in the team's expert opinion to be important in a commercial operational context, and ranked in a qualitative way. Table 9-12 must be treated with caution but nevertheless indicates that feedstock characteristics are not affected in a consistent way by the site properties and crop management. As was found for poplar SRF, the results for spruce SRF imply that growers have a reasonable degree of control over many of the most important influences on feedstock properties. For example, the most important factor affecting moisture and NCV, i.e. storage, can be manipulated and storage also is an important determinant of many macronutrients. Many of the other properties can be adjusted by the choice of the plant part to market and in a couple of cases the harvest time. Climate zone was the second ranked influence on chlorine in trunk wood but the chlorine levels in our samples were so low that this had little operational relevance. Feedstock properties were relatively insensitive to the way conifer SRF was grown. The implications for buyers are that consideration must be given to the feedstock characteristics of prime importance in a particular application.

Although spruce SRF sites were geographically the farthest apart and the climate zones investigated were warm moist vs. cold wet, there was little impact of climate zone. At first glance this may seem surprising but can be explained as follows. Firstly, climate zone is based on 30-year average weather observations and the actual conditions during the growth of the crops in the two zones may not have been sufficiently different to affect the trees growth rate either because of chance weather patterns or because of local factors, e.g. altitude, aspect,

and shelter, which may have minimised the differences in conditions experienced between sites. Secondly, temperature or moisture availability are likely to affect growth rate (which was not assessed as part of the project) and total uptake of nutrients and other elements but are not likely to affect the concentrations of nutrients and other elements directly. Finally, the number of samples was comparatively small and may not have been sufficient to detect differences.

Table 9-12: Factors influencing key feedstock characteristics of spruce SRF ranked in order of decreasing importance.

Variable	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7
Moisture % wt (ar)	Storage	Harvest time	Plant part	Soil type	Climate zone		
NCV, kJ/kg (ar)	Storage	Harvest time	Plant part	Soil type	Climate zone		
Ash, %wt (d)	Plant part	Storage	Harvest time	Crop age	Soil type	Climate zone	
Nitrogen, %wt (DAF)	Plant part	Storage	Harvest time	Soil type	Planting density = Crop age		Climate zone
Sulphur, %wt (DAF)	Plant part	Storage=Harvest time		Soil type	Climate zone		
Chlorine, % wt (DAF)	Plant part	Climate zone	Soil type	Harvest time	Storage		
Al_2O_3, %wt (na)	Plant part	Storage	Harvest time	Climate zone	Soil type		
MgO (na)	Plant part	Harvest time	Climate zone	Soil type	Storage		
Na_2O, %wt (na)	Plant part	Harvest time	Climate zone	Storage	Soil type		
P_2O_5, wt% (d)	Plant part	Storage	Soil type	Climate zone	Harvest time		
SiO_2, wt% (d)	Plant part	Storage	Harvest time	Climate zone	Soil type		
Ca, mg/kg (d)	Plant part	Storage	Harvest time	Soil type	Climate zone		
K, mg/kg (d)	Plant part	Storage	Harvest time	Soil type	Climate zone		
Mn, mg/kg (d)	Plant part	Storage	Harvest time	Soil type	Climate zone		
Na, mg/kg (d)	Plant part	Harvest time	Climate zone	Storage	Soil type		
P, mg/kg (d)	Plant part	Storage	Harvest time	Soil type	Climate zone		
Si, mg/kg (d)	Plant part	Storage	Harvest time	Climate zone	Soil type		
Alkali Index	Plant part	Storage	Climate zone	Harvest time	Soil type		

9.5 Comparison of different plant parts

In general, most chemical parameters were found at higher concentrations in the tops and bark than in the trunk parts of the spruce SRF. In general concentrations in the bark were broadly similar to those in the tops, which was somewhat unexpected as it is commonly assumed that the bark will have the highest concentrations of elements. The ash content of trunk wood was approximately 0.5% (dry), with that in the tops and bark being approximately five times higher (see Figure 9-4). The increase in ash content also results in higher mineral and trace element concentrations in the feedstock.

Dry Nitrogen concentrations (Figure 9-7) in the trunk wood averaged approximately 0.25%, with those in the tops at approximately 0.8% and the bark slightly lower at 0.6%. Sulphur and chlorine were not detectable in most of the trunk samples, with levels of both about 0.04% in the tops and slightly lower in the bark.

Concentrations of trace and macroelements in the three plant parts showed interesting behaviour – in general levels in the tops and bark were similar and higher than those seen in the trunk (e.g. phosphorous, Figure 9-11) but for certain elements including, barium, zinc, bromine and calcium (see Figure 9-10) levels were notably higher in the bark than seen in the tops. A handful of elements including lead (Figure 9-8), fluorine, aluminium and iron appeared at similar concentrations in all three plant parts. Finally, silicon showed unusual behaviour, being present in the bark at only marginally higher concentrations than the trunk parts, with the tops containing the highest concentrations of all (Figure 9-5). It was assumed prior to this exercise that silicon would be highest in the bark due to the potential for soil entrapment in the bark and contamination during harvesting; the data from this exercise suggest that the latter may be significant and the careful procedures used to avoid this source in this project were effective. Graphs for all the feedstock parameters are provided in Appendix 13.

9.6 Conclusions

- *With the exception of Miscanthus, the feedstocks are differentiated into plant parts that have different functions, e.g. mechanical support versus photosynthesis; therefore we hypothesise that these plant parts will differ in their fuel properties and/or composition.* The composition of the spruce SRF trunk, tops and bark clearly demonstrated differences between them, as discussed in Section 9.5. However, the differences between the spruce SRF bark and tops were not as significant as expected.

- *Feedstock properties will differ depending on the climate the crop is exposed to.* Relatively few feedstock parameters showed significant statistical impacts due to climate zone; although climate zone was the second ranked influence on chlorine in trunk wood, the chlorine levels in these samples were so low that this had little operational relevance. This may be due to a lack of actual difference in growing conditions during the crop's development; to the expectation that differences would be indirect through the impact of growing conditions on growth rate and therefore limited in magnitude; and the comparatively limited sample size.

- *Feedstock properties will differ depending on the soil composition and characteristics of the site*. Only one impact of soil type was observed for the spruce SRF samples; for P_2O_5 in the bark.

- *Feedstock properties will differ according to the time of year that the biomass is harvested.* A number of feedstock characteristics did vary with harvest time, though this

was more evident in the tops than the trunk. For the spruce SRF trunk, a number of macroelements decreased in the second harvest. The spruce SRF bark was most impacted by harvest time, but apart from some small changes in NCV and certain macroelements, the majority of the impacts were operationally insignificant.

- *Feedstock properties will differ with storage.* Storage had the largest number of impacts on the spruce SRF tops and trunk, with strong effects on moisture (and hence NCV), as well as for a number of other parameters. For the spruce SRF tops, decreases in ash, nitrogen chlorine and certain macroelements were also noted in the stored material, while lead appeared to increase.

The planting density and the age of the sampled material did explain a significant proportion of the variation in some of the spruce SRF trunks and tops feedstock characteristics (see Appendix 13), although impacts varied. For example barium concentrations in spruce SRF trunk wood tended to decrease as planting density increased, while for the spruce SRF tops, nitrogen levels increased in older samples.

Correlation analysis between the soil properties and the feedstock characteristics showed few relationships between the feedstock and soil characteristics; of those that were observed, available zinc in the soil seemed to have the most influence.

A qualitative ranking of factors affecting the characteristics of spruce SRF imply that growers have a reasonable degree of control over many of the most important influences on feedstock properties. For example, the most important factor affecting moisture and NCV, i.e. storage, can be manipulated and storage also was a second rank determinant of many macronutrients. Many of the other properties can be adjusted by the choice of the plant part to market and in a couple of cases the harvest time. Climate zone was the second ranked influence on chlorine in trunk wood but the chlorine levels in our samples were so low that this had little operational relevance. Feedstock properties were relatively insensitive to the way conifer SRF was grown. The implications for buyers are that consideration must be given to the feedstock characteristics of prime importance in a particular application.

10 Comparison with External Datasets

The focus of this project was on the characterisation of different biomass feedstocks and hence the focus of the comparison with external datasets has been on this basis. However, many different soil samples have also been analysed and generated useful data, so these data are also briefly discussed in this section.

10.1 Biomass data comparison

The Phyllis2 database is probably the biggest and most robust of the few external datasets that contain information on the physical and chemical properties of a range of biomass and waste materials. It is managed by ECN (Energy Research Centre of the Netherlands) and draws together results from many sources and countries. Although different results may not be directly comparable, owing to different sources, conditions and analysis techniques, it is the most comprehensive database of such measurements available in the public domain. It has therefore been used to compare the results from this project and to highlight any that differ significantly.

The Phyllis2 database draws data together from a variety of other sources and papers and hence, for most data entries, there may be a further level of detailed information (e.g. on sampling and analysis methods, maturity of sampled biomass, time of sampling etc.) that can be gleaned by consulting the original publications from which the original data were sourced. However, such detailed investigation of raw data was beyond the scope of this work and the intention here was simply to confirm whether any measurements in this study were significantly different from those reported in the database. This was done by comparison of the mean values and standard deviation for each parameter. For certain species and analysis parameters, the number of datasets reported by Phyllis2 was low and where the number of measurements for a given parameter was less than three, the data have not been compared.

Within this project there are separate datasets for different plant parts (such as trunks and tops) and these have been discussed separately. In many cases, the origin of the Phyllis2 sample is unclear, and apart from some exceptions (e.g. spruce bark is reported separately), it has to be assumed that the data refers to mixed material.

Only the analyses of freshly harvested samples from this project have been considered in this comparison exercise. The entries in the Phyllis2 database do not, in general, specify whether they refer to fresh or stored samples. It is assumed that the majority are fresh samples; however it is likely that the database includes samples which have been stored and/or pre-dried, as some data entries indicate a relatively low moisture content. Given the sensitivity of moisture content (and also Net CV) to the specific climatic conditions prior to, and at the time of sampling and also how the samples were handled before analysis, these values are expected to show significant variation between the two datasets and are not considered in this analysis. All of the other parameters have been compared on a dry or dry ash free (DAF) basis which effectively normalises for moisture (or moisture and ash) and allows comparison on an equal basis.

In addition, there will be different experimental and reporting practices which may influence any comparisons. For example, for the macroelements it is common practice to report each element as the percentage of the equivalent oxide in the ash, however it has been determined that much of the calcium in biomass ash appears to be present as $CaCO_3$ rather than CaO. For this project the percentage of calcium in ash has therefore been expressed throughout as

the carbonate rather than the oxide. However, in order to make the comparison with the Phyllis2 data it has been expressed as the oxide for this exercise. Similarly, for this project, the ash oxide values have always been normalised to 100% on an SO_3-free basis, as is the normal convention. It is not clear whether all the Phyllis2 ash oxide data is normalised, or even whether the same set of elements were included in the calculation. Different laboratories and research groups will also take different approaches to the reporting of values below the limit of detection (LOD); while the data in this report assumes <LOD results to be at the LOD, other sources may report these as zero or a value between zero and the LOD. Note also that LODs will vary between laboratories.

The comparison has been undertaken between the mean value of the freshly harvested samples for each feedstock (and plant part where appropriate) from the Deliverable D4 dataset and mean of comparable values from Phyllis2. The threshold for triggering a 'significant' difference is where the mean value for this work lies outside more than one standard deviation (SD) of the Phyllis2 data – these cells are highlighted in pink in the following tables. Where the difference between the D4 mean value and that from Phyllis is less than 1SD the values are regarded as consistent, so in the following text any differences noted are those for which the difference is at least 1SD above or below the Phyllis value.

10.1.1 *Miscanthus*

The Phyllis2 database contains a number of different categories under the entry *Miscanthus* and those that were selected were judged to be representative of fresh samples appropriate for comparison with the data generated from this study.

Good agreement was seen for the majority of characteristics, with the vast majority showing a difference of less than one standard deviation between two datasets. Table 10-1 provides the comparison and highlights particularly good agreement for the standard proximate and ultimate fuel analysis on the two datasets with the exception of fluorine, noting that only four results were available from Phyllis2 for comparison.

In general, agreement for the trace elements was also very good, only the data for chromium, nickel and vanadium were different by more than the 1SD threshold, again noting there were only four results were available from Phyllis2.

The ash composition also shows good agreement, with only P_2O_5, CaO and Na_2O concentrations in ash showing significant differences of >1SD; all these elements are higher in this dataset compared to Phyllis2. Agreement was less satisfactory for the macroelements expressed as the element in the fuel, but for most of the elements expressed on this basis there were only three entries in Phyllis2.

Table 10-1: Comparison of *Miscanthus* data mean values and standard deviation (SD) from this project and Phyllis2 database

Variable	Units (basis)	Phyllis2 Database results			Results from this project	
		Mean	SD	Samples	Mean	SD*
Ash content	wt% (dry)	**3.9**	1.64	43	**2.3**	-0.97
Volatile matter	wt% (DAF)	**82.2**	6.19	9	**82.7**	0.08
Carbon	wt% (DAF)	**49.49**	1.31	53	**49.81**	0.24
Hydrogen	wt% (DAF)	**5.68**	0.35	53	**6.04**	1.01
Nitrogen	wt% (DAF)	**0.55**	0.3	53	**0.40**	-0.50
Sulphur	wt% (DAF)	**0.08**	0.08	51	**0.01**	-0.85
Gross calorific value	kJ/kg (DAF)	**19,780**	600	52	**19,651**	-0.22
Chlorine (Cl)	wt% (DAF)	**0.23**	0.13	51	**0.14**	-0.75
Fluorine (F)	mg/kg (dry)	**20.2**	9.5	4	**2.431**	-1.87
Arsenic (As)	mg/kg (dry)	**0.80**	0.8	3	**0.03**	-0.96
Barium (Ba)	mg/kg (dry)	**4.30**	3.4	3	**7.62**	0.98
Cadmium (Cd)	mg/kg (dry)	**0.100**	0.2	29	**0.050**	-0.25
Chromium (Cr)	mg/kg (dry)	**1.70**	0.9	4	**0.23**	-1.63
Cobalt (Co)	mg/kg (dry)				**0.11**	
Copper (Cu)	mg/kg (dry)	**2.20**	1.2	31	**1.87**	-0.28
Manganese (Mn)	mg/kg (dry)	**29.80**	35	4	**39.92**	0.29
Mercury (Hg)	mg/kg (dry)	**0.000**	0.1	28	**0.004**	0.04
Molybdenum (Mo)	mg/kg (dry)				**0.21**	
Nickel (Ni)	mg/kg (dry)	**1.60**	0.7	4	**0.13**	-2.10
Lead (Pb)	mg/kg (dry)	**2.400**	2.2	29	**0.381**	-0.92
Vanadium (V)	mg/kg (dry)	**0.40**	0.1	4	**0.12**	-2.84
Zinc (Zn)	mg/kg (dry)	**17.50**	10.7	4	**15.23**	-0.21
Al_2O_3	wt% (ash)	**0.41**	0.38	33	**0.48**	0.17
CaO	wt% (ash)	**5.80**	1.92	33	**8.87**	1.60
Fe_2O_3	wt% (ash)	**0.36**	0.26	33	**0.31**	-0.19
K_2O	wt% (ash)	**15.88**	10.25	33	**19.68**	0.37
MgO	wt% (ash)	**3.10**	1.19	33	**3.22**	0.10
Na_2O	wt% (ash)	**0.29**	0.37	33	**0.84**	1.48
P_2O_5	wt% (ash)	**2.79**	1.1	33	**6.36**	3.25
SiO_2	wt% (ash)	**60.81**	16.16	33	**52.73**	-0.50
TiO_2	wt% (ash)				**0.09**	
Aluminium (Al)	mg/kg (dry)	**126**	49.9	3	**57.8**	-1.37
Calcium (Ca)	mg/kg (dry)	**1463**	811.2	3	**1130**	-0.41
Iron (Fe)	mg/kg (dry)	**117**	66.2	3	**44.8**	-1.09
Potassium (K)	mg/kg (dry)	**8622**	5086	6	**3185**	-1.07
Magnesium (Mg)	mg/kg (dry)	**572**	110.9	3	**341**	-2.08
Sodium (Na)	mg/kg (dry)	**249**	127	6	**126**	-0.96
Phosphorus (P)	mg/kg (dry)	**620**	121.7	3	**509.7**	-0.91
Silicon (Si)	mg/kg (dry)	**6,967**	4248	3	**5,025**	-0.46
Titanium (Ti)	mg/kg (dry)	**6.4**	2.6	3	**10.93**	1.74

* standard deviation from the Phyllis2 dataset

10.1.2 Willow SRC

As with *Miscanthus*, the Phyllis2 database contains a number of different categories under the entry for willow but does not make clear whether these samples refer to mature willow grown as single-stem, or SRC (and if SRC, which harvest cycle). Samples from mature trees may be expected to have a lower ratio of bark to stemwood than the very much more slender stems from SRC samples. Owing to the significant differences between stem wood and bark this may be expected to have a significant impact on the observed properties. Despite this uncertainly, all of the willow datasets were selected as appropriate for comparison with the data generated from this project. The differences between the measurements reported here and the values extracted from Phyllis2 are, in general, relatively minor (see Table 10-2). Again good agreement was seen for the standard fuel proximate and ultimate analysis with only sulphur showing a difference of >1SD (lower in this dataset compared to Phyllis2). For the trace elements, a large difference in manganese concentrations was noted, whilst cadmium was also highlighted, with the remaining elements all agreeing within 1SD. However, for certain elements in the Phyllis2 dataset the standard deviation was very high indeed, emphasising the variability of the data. The ash composition data was also comparable with only the data for Na_2O and MgO falling outside the >1SD threshold. For the macroelements expressed as their concentration in the fuel, all the data fell within the <1SD criteria.

Table 10-2: Comparison of willow data mean values and standard deviation (SD) from this project and Phyllis2 database

Variable	Units (basis)	Phyllis2 Database results			Results from this project	
		Mean	SD	Samples	Mean	SD*
Ash content	wt% (d)	2.0	0.93	24	1.8	-0.17
Volatile matter	wt% (DAF)	83.5	2.35	20	82.9	-0.29
Carbon	wt% (DAF)	49.80	1.2	24	50.48	0.57
Hydrogen	wt% (DAF)	6.10	0.19	24	6.19	0.46
Nitrogen	wt% (DAF)	0.62	0.3	25	0.61	-0.04
Sulphur	wt% (DAF)	0.05	0.03	20	0.01	-1.22
Gross calorific value	kJ/kg (DAF)	19,840	720	24	20,074	0.33
Chlorine (Cl)	wt% (DAF)	0.02	0.01	13	0.02	0.62
Fluorine (F)	mg/kg (d)	26.3	42.2	5	1.063	-0.60
Cadmium (Cd)	mg/kg (d)	2.3	0.7	4	0.959	-1.92
Chromium (Cr)	mg/kg (d)	11.1	15.6	7	0.22	-0.70
Copper (Cu)	mg/kg (d)	6.3	3.8	6	4.36	-0.51
Manganese (Mn)	mg/kg (d)	12.2	7.1	7	52.39	5.66
Nickel (Ni)	mg/kg (d)	23.6	25.4	7	0.71	-0.90
Lead (Pb)	mg/kg (d)	96	114.1	4	0.594	-0.84
Vanadium (V)	mg/kg (d)	0.2	0.1	3	0.17	-0.30
Zinc (Zn)	mg/kg (d)	98.1	28.1	7	88.20	-0.35
Al_2O_3	mg/kg (d)	1.1	0.97	14	0.63	-0.48
CaO	mg/kg (d)	36.47	5.58	14	34.41	-0.37
Fe_2O_3	mg/kg (d)	0.55	0.35	14	0.45	-0.29
K_2O	mg/kg (d)	15.98	4.46	14	16.29	0.07
MgO	mg/kg (d)	3.52	1.72	14	5.35	1.06
Na_2O	wt% (na)	1.8	1.02	14	0.48	-1.29
P_2O_5	wt% (na)	9.51	1.87	14	11.26	0.94

Variable	Units (basis)	Phyllis2 Database results			Results from this project	
		Mean	SD	Samples	Mean	SD*
SiO_2	wt% (na)	7.62	9.03	14	3.50	-0.46
TiO_2	wt% (na)	0.05	0.04	13	0.07	0.50
	wt% (na)					
Aluminium (Al)	wt% (na)	57.2	32.9	6	63.2	0.18
Calcium (Ca)	wt% (na)	5,409	1302.9	7	4,161	-0.96
Iron (Fe)	wt% (na)	58.0	29.4	7	62.3	0.15
Potassium (K)	wt% (na)	2,702	855.6	9	2,380	-0.38
Magnesium (Mg)	mg/kg (d)	498	112.1	7	550	0.46
Sodium (Na)	mg/kg (d)	186	139.7	8	59.6	-0.90
Phosphorus (P)	mg/kg (d)	782	203.2	7	854	0.35
Silicon (Si)	mg/kg (d)	445	626.7	7	330	-0.18
Titanium (Ti)	mg/kg (d)	3.6	3.1	5	6.7	0.99

* standard deviation from the Phyllis2 dataset

10.1.3 Poplar

There are relatively few entries for poplar in the Phyllis2 database. As with the willow there is no indication of the age of the samples, nor are any details of the plant parts included in the samples. Owing to the shortage of poplar SRC data from this study, only the data obtained from the poplar SRF samples have been compared here. As noted in Section 2.3, the poplar SRF samples taken for this project were separated into trunk and tops. The trunk will consist primarily of wood, with a smaller proportion of bark than the tops, which will also include twigs and small branches. In addition the tops will have possibly contained a few leaves for harvest 1 (April), and probably significant leaf for harvest 2 (July). The results from this study are therefore split into harvest 1 and harvest 2 (see Table 10-3). It is generally found that bark, and especially leaves, contain much higher levels of the minerals that contribute to ash than wood, especially heartwood which contains little vascular tissue and metabolites. Assuming that the Phyllis2 data is from a mixture of poplar plant parts, it would therefore be expected that the trunk samples from this study to be similar to, or lower than the Phyllis2 data for most elements, but the tops to be higher, especially those from harvest 2. It should be noted that there were virtually no data for trace elements in the Phyllis2 database, neither were there any data for fluorine or macroelements expressed as concentration in the fuel.

10.1.3.1 Trunk

In general, the analysis data for the trunk agreed very closely with the Phyllis2 data, i.e. within 1SD; the results are presented in Table 10-3. The notable exceptions, which were consistent across both harvests, were for sulphur and Na_2O. Sulphur was slightly lower in the dataset from this project, whilst sodium was higher.

10.1.3.2 Tops

As might be expected from the above comments, there are considerably more cells highlighted against poplar tops where the two datasets are different by >1SD. The tops samples from harvests 1 and 2 in this project were considerably higher in total ash content (difference up to 6.1 SD), and this was also reflected in higher levels of many individual elements compared to the Phyllis2 database values. The higher ratio of bark to wood in the tops may be expected to be the main reason for the higher ash content in the samples from the first harvest compared

to the trunk samples, with the significant further increase in the H2 samples due to the inclusion of leaves.

Nitrogen levels in the tops were also much higher than the Phyllis2 dataset (more so for harvest 2), whilst the sulphur content for harvest 2 was also significantly higher – both these observations probably reflect the inclusion of leaves in the harvest 2 sample. Carbon and hydrogen were also slightly higher – this increased the DAF Gross CV compared to the Phyllis2 data.

In terms of ash composition, Na_2O concentrations, were again significantly higher than the Phyllis2 average, considerably more so for harvest 1 than harvest 2, which was actually lower than in the equivalent trunk sample. The only other species showing a difference >1SD was Fe_2O_3, which appeared at slightly lower concentrations than in the Phyllis2 dataset.

Given the good agreement between the trunk dataset and Phyllis2 and the differences observed for the tops dataset, it is judged that the vast majority of the Phyllis2 poplar data was derived from analysis of samples that were dominated by trunk parts, and as such are not directly comparable with the tops data from this project (which contains smaller branches and, for the second harvest, leaves).

Table 10-3: Comparison of poplar data mean values and standard deviation (SD) from this project (SRF feedstocks) and Phyllis2 database

Variable	Units (basis)	Phyllis2 Database results			Harvest 1 Results				Harvest 2 Results			
		Mean	SD	Samples	Trunks		Tops		Trunks		Tops	
					Mean	SD*	Mean	SD*	Mean	SD*	Mean	SD*
Ash content	wt% (d)	1.3	0.69	17	1.6	0.48	3.4	3.14	1.5	0.31	5.5	6.06
Volatile matter	wt% (DAF)	82.6	6.11	6	84.2	0.27	81.3	-0.21	84.5	0.32	80.4	-0.36
Carbon	wt% (DAF)	49.78	1.92	13	49.96	0.09	51.06	0.67	50.33	0.29	52.17	1.24
Hydrogen	wt% (DAF)	6.05	0.2	13	6.13	0.39	6.25	1.01	6.12	0.35	6.24	0.94
Nitrogen	wt% (DAF)	0.39	0.28	11	0.30	-0.34	0.87	1.73	0.32	-0.26	1.33	3.34
Sulphur	wt% (DAF)	0.03	0.02	10	0.01	-1.00	0.01	-0.95	0.01	-1.00	0.12	4.64
Gross calorific value	kJ/kg (DAF)	19,980	550	11	19,847	-0.24	20,567	1.07	19,787	-0.35	20,716	1.34
Chlorine (Cl)	wt% (DAF)	0.03	0.039	9	0.01	-0.62	0.02	-0.29	0.01	-0.55	0.04	0.06
Al_2O_3	wt% (na)	1.23	1.37	4	1.02	-0.16	0.18	-0.76	0.76	-0.35	0.30	-0.68
CaO	wt% (na)	42.71	9.26	4	37.92	-0.52	38.77	-0.43	38.82	-0.42	35.46	-0.78
Fe_2O_3	wt% (na)	0.76	0.57	3	0.41	-0.62	0.19	-1.01	0.29	-0.83	0.13	-1.11
K_2O	wt% (na)	16.20	7.19	4	15.82	-0.05	14.13	-0.29	14.87	-0.18	18.56	0.33
MgO	wt% (na)	8.61	8.06	4	5.35	-0.40	5.69	-0.36	5.30	-0.41	5.31	-0.41
Na_2O	wt% (na)	0.22	0.14	4	0.45	1.63	0.79	4.05	0.50	2.01	0.41	1.38
P_2O_5	wt% (na)	5.43	8.14	3	5.56	0.02	8.47	0.37	5.70	0.03	7.39	0.24
SiO_2	wt% (na)	5.33	4.2	3	3.49	-0.44	1.18	-0.99	2.20	-0.75	4.42	-0.22

* standard deviation from the Phyllis2 dataset

10.1.4 Spruce

It is assumed that the majority of the Phyllis2 samples are likely to be from mature spruce, while all those reported in this project are from relatively young Sitka trees (around 15-years old) as an SRF analogue. Note that in most cases Phyllis2 does not identify which species of spruce has been sampled. In a similar way to the poplar SRF samples, spruce SRF samples reported in this project were divided into de-barked trunk, tops and the bark which were all analysed separately. The Phyllis2 database does include data on spruce bark, and consequently a direct comparison with these was possible, while the (bark free) trunks and the tops were compared with the generic Phyllis2 spruce values. It is considered likely that the Phyllis2 samples will be a mixture of trunk and tops and likely to include a proportion of bark. As with the poplar data, it might therefore be expected that the concentrations of ash and most elements to be lower in the de-barked trunk and hence be lower than the values reported in Phyllis2, but higher for the tops. As spruce is an evergreen conifer with needles in the tops samples from both harvests, the difference between harvest times H1 and H2 might be expected to be less significant for some minerals than the deciduous poplar tops (which contained negligible leaves in the samples from the first harvest, but significant leaf content from the second). The immediate impression from the data comparisons is that unlike the other feedstocks, the majority of the data shows >1SD difference between the two datasets – see Table 10-4.

10.1.4.1 Trunk wood

The ash content of the bark-free trunk samples from this project was marginally, though not significantly, lower than the Phyllis2 database. This change was reflected in the lower values of the vast majority of trace elements and macro elements/oxides in ash, with the exception of the percentages of K_2O, MgO and P_2O_5 in the ash, which were all higher. The majority of the carbon, hydrogen and nitrogen values were higher, as was DAF Gross CV than the Phyllis2 data, whilst the sulphur values were slightly lower.

10.1.4.2 Tops

The ash content of the tops from this study was significantly higher than the Phyllis2 dataset. Volatile matter was also notably lower, whilst carbon and hydrogen contents were higher, reflecting in the higher DAF Gross CV. Nitrogen and chlorine values in the tops were considerably higher than the Phyllis2 data.

While trace element content would be expected to correlate with ash content, for most elements concentrations in the project dataset were lower than those in Phyllis2. Partially this is because the averages in Phyllis2 are derived from different numbers of samples for each species. Of the six Phyllis2 samples contributing the majority of data for the major element concentrations in fuel, five are described as “logging residues”. These samples averaged 3.2 wt% ash (dry), i.e. were higher in ash than the spruce tops samples from this study; it is likely that much of the logging residue consisted of tops material. Similarly, these five logging residue sample also contributed the majority of the data for many of the trace element species. The proportions of oxides in the ash also varied (note that these are independent of overall ash content), with K_2O, MgO, Na_2O and P_2O_5 appearing at higher percentages than in the Phyllis2 values, and all other oxides appearing at lower concentrations.

10.1.4.3 Spruce bark

Although spruce bark was considered separately in the Phyllis2 database, there were only eight entries in total, and many of these did not have full set of characterisation data. As a

result, many feedstock parameters could not be compared as there were insufficient entries from which to calculate mean values, this included virtually all trace elements and ash oxides – see Table 10-5.

Nitrogen and chlorine levels were higher in the bark from this study compared to the Phyllis2 data, whilst that for sulphur was lower. The differences for harvest 1 were greater than harvest 2. For the trace elements, cadmium was lower in this dataset compared to Phyllis 2 whilst for the other two trace elements the differences were within 1SD. However, the high standard deviation for other trace elements in the Phyllis2 dataset should be noted.

Table 10-4: Comparison of spruce SRF trunks and tops data mean values and standard deviation (SD) from this project (SRF feedstocks) and Phyllis2 database

Variable	Units (basis)	Phyllis2 Database results			Harvest 1 Results				Harvest 2 Results			
					Trunks (bark free)		Tops		Trunks (bark free)		Tops	
		Mean	SD	Samples	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ash content	wt% (d)	0.85	0.83	23	0.6	-0.36	2.4	1.84	0.3	-0.61	2.4	1.84
Volatile matter	wt% (DAF)	84.8	2.68	6	84.5	-0.14	78.8	-2.27	84.8	-0.01	78.3	-2.45
Carbon	wt% (DAF)	49.31	1.21	24	49.88	0.47	53.44	3.41	50.59	1.06	53.83	3.74
Hydrogen	wt% (DAF)	5.90	0.16	24	6.24	2.14	6.50	3.77	6.20	1.85	6.42	3.26
Nitrogen	wt% (DAF)	0.17	0.1	22	0.31	1.38	0.97	8.02	0.21	0.37	0.89	7.16
Sulphur	wt% (DAF)	0.03	0.02	17	0.01	-1.00	0.03	0.00	0.01	-1.00	0.05	1.04
Gross calorific value	kJ/kg (DAF)	19,240	760	23	20,125	1.16	21,914	3.52	20,107	1.14	21,602	3.11
Chlorine (Cl)	wt% (DAF)	0.01	0.01	8	0.01	-0.12	0.05	2.92	0.01	-0.40	0.04	2.14
Arsenic (As)	mg/kg (d)	0.10	0.1	3	0.01	-0.94	0.01	-0.87	0.003	-0.97	0.02	-0.85
Barium (Ba)	mg/kg (d)	73.20	30.2	5	19.54	-1.78	33.29	-1.32	13.01	-1.99	30.72	-1.41
Cadmium (Cd)	mg/kg (d)	0.300	0.1	8	0.03	-2.71	0.04	-2.65	0.03	-2.72	0.10	-1.97
Chromium (Cr)	mg/kg (d)	2.80	0.9	5	0.14	-2.95	0.38	-2.68	0.10	-3.00	0.35	-2.73
Cobalt (Co)	mg/kg (d)	0.30	0.1	5	0.03	-2.67	0.12	-1.76	0.03	-2.71	0.12	-1.81
Copper (Cu)	mg/kg (d)	3.80	3.1	8	1.53	-0.73	3.98	0.06	1.47	-0.75	3.73	-0.02
Manganese (Mn)	mg/kg (d)	349.2	230.5	6	60.96	-1.25	373.3	0.10	49.28	-1.30	397.4	0.21
Nickel (Ni)	mg/kg (d)	1.80	0.9	5	0.15	-1.83	0.75	-1.17	0.10	-1.89	0.65	-1.28
Lead (Pb)	mg/kg (d)	2.200	1.8	9	0.711	-0.83	0.463	-0.97	0.137	-1.15	0.496	-0.95
Vanadium (V)	mg/kg (d)	0.60	0.3	5	0.06	-1.80	0.23	-1.25	0.02	-1.92	0.21	-1.29
Zinc (Zn)	mg/kg (d)	105.2	51	6	9.32	-1.88	33.93	-1.40	7.13	-1.92	30.66	-1.46
Al_2O_3	wt% (na)	1.50	1.69	4	1.93	0.25	1.01	-0.29	2.22	0.42	1.25	-0.15
CaO	wt% (na)	36.43	5.28	4	28.86	-1.43	25.34	-2.10	30.97	-1.03	25.52	-2.07
Fe_2O_3	wt% (na)	1.29	1.01	4	1.43	0.14	0.50	-0.78	1.03	-0.26	0.54	-0.74
K_2O	wt% (na)	9.48	3.1	4	22.32	4.14	21.45	3.86	18.08	2.77	18.19	2.81
MgO	wt% (na)	3.72	1.07	4	6.68	2.77	8.01	4.01	8.39	4.36	7.19	3.24
Na_2O	wt% (na)	0.39	0.28	4	0.38	-0.04	0.84	1.60	0.27	-0.43	0.74	1.25
P_2O_5	wt% (na)	3.16	0.86	4	5.77	3.03	9.43	7.29	6.82	4.25	11.13	9.27
SiO_2	wt% (na)	18.48	7.25	4	7.90	-1.46	11.21	-1.00	3.98	-2.00	11.19	-1.01

Variable	Units (basis)	Phyllis2 Database results			Harvest 1 Results				Harvest 2 Results			
					Trunks (bark free)		Tops		Trunks (bark free)		Tops	
		Mean	SD	Samples	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Aluminium (Al)	mg/kg (d)	150.3	60.8	6	55.15	-1.56	110.3	-0.66	33.40	-1.92	121.3	-0.48
Calcium (Ca)	mg/kg (d)	7321	3589.5	6	968.7	-1.77	3,815	-0.98	586.0	-1.88	3,372	-1.10
Iron (Fe)	mg/kg (d)	242.3	225.3	6	65.90	-0.78	70.90	-0.76	21.27	-0.98	69.04	-0.77
Potassium (K)	mg/kg (d)	1625	1085.7	6	861.5	-0.70	3,777	1.98	407.7	-1.12	2,799	1.08
Magnesium (Mg)	mg/kg (d)	532.3	245.5	6	191.3	-1.39	1,004	1.92	135.5	-1.62	787.7	1.04
Sodium (Na)	mg/kg (d)	95.3	86.3	3	17.04	-0.91	146.6	0.59	5.42	-1.04	101.2	0.07
Phosphorus (P)	mg/kg (d)	437	316.5	6	126.9	-0.98	809.5	1.18	82.71	-1.12	888.4	1.43
Silicon (Si)	mg/kg (d)	2131	1331.9	5	216.7	-1.44	1,138	-0.75	53.71	-1.56	1,116	-0.76
Titanium (Ti)	mg/kg (d)	12.3	8.3	3	5.79	-0.78	2.50	-1.18	1.17	-1.34	6.44	-0.71

Table 10-5: Comparison of spruce SRF bark data mean values and standard deviation (SD) from this project (SRF feedstocks) and Phyllis2 database

Variable	Units (basis)	Phyllis2 Database results			Harvest 1 Results		Harvest 2 Results	
		Mean	SD	Samples	Mean	SD	Mean	SD
Ash content	wt% (d)	2.9	0.98	4	2.4	-0.57	2.2	-0.72
Volatile matter	wt% (DAF)	74.2	2.44	3	74.2	0.00	74.6	0.14
Carbon	wt% (DAF)	52.98	2.03	7	53.84	0.42	54.05	0.53
Hydrogen	wt% (DAF)	5.79	0.47	7	6.15	0.76	6.04	0.54
Nitrogen	wt% (DAF)	0.45	0.13	6	0.63	1.38	0.54	0.68
Sulphur	wt% (DAF)	0.04	0.02	6	0.01	-1.50	0.02	-1.05
Gross calorific value	kJ/kg (DAF)	20,820	780	7	21,601	1.00	21,183	0.47
Chlorine (Cl)	wt% (DAF)	0.02	0.01	5	0.04	2.56	0.03	1.55
Cadmium (Cd)	mg/kg (d)	0.8	0.5	3	0.173	-1.25	0.142	-1.32
Copper (Cu)	mg/kg (d)	5.10	1.8	3	4.61	-0.27	4.09	-0.56
Lead (Pb)	mg/kg (d)	15.3	18.6	4	0.487	-0.80	0.502	-0.80

10.2 Soil data comparison

Over 50 different soil samples were analysed during the course of the project, with a (composite) soil sample collected for each site in studies 1-3. Some of these data (specifically for trace elements) have been briefly compared with data provided by the UK Soil and Herbage Pollutant Survey (UKSHS) (Ross *et al.*, 2007) and British Geological Survey (BGS) (Ander *et al.*, 2013).

Table 10-6 shows the mean values for seven trace elements analysed for the UKSHS grouped into three classifications (rural, urban and industrial settings) as well as the range of normal background concentration (NBC) reported by BGS. These values have been compared with the mean obtained from soil samples from this project. However, on closer investigation, it was noted that certain willow SRC sites that were only sampled for leaves appeared to contain much higher levels of trace elements in the soil than any other sites investigated. As a result the data from this study has been reported on two bases, including and excluding these sites.

The soil data suggests that when the leaves-only sites are excluded, the majority of soils at sites utilised by this project contained below-average concentrations of trace metals even for UKSHS 'rural' sites. Even when the leaves-only sites were included in the average, only the value for mercury increases to above what would be expected for a 'rural' site. This indicates that the sites selected for use in this project were relatively uncontaminated and should be considered as representative of typical agricultural and forestry sites given over to each of the five bio-energy crops. It should be noted that no remediated or reclaimed sites were included in the sampling design therefore the results should not be extrapolated to these sites where much higher levels of trace elements would be expected.

While it appears that soil phosphate levels were higher in the medium soils within this project, the reason for this is unclear. Phosphorous in cultivated soils is largely found in the inorganic form and so is not mobile or available to most plants, hence the requirement for applied phosphate fertilisers, and does not become available to plants until it is mineralized. Organic phosphorous is required by plants. Medium soils could typically contain more base inorganic phosphorous levels because they have a higher percentage of clay and or silt content which can hold the positively charged element, however, this does not automatically mean these soils will have more organic phosphate available to the plant.

Table 10-6: Comparison of reference soil metal levels with soil data from project

Metal	Rural	Urban	Industrial	NBC*	Project Mean (excluding willow SRC leaves only sites)**	Project Mean (all feedstocks)
Arsenic (mg/kg)	10.9	11	18.1	32-290	6.4	8.86
Cadmium (mg/kg)	0.39	0.44	1.33	N/A	0.16	0.22
Chromium (mg/kg)	34.4	34.3	41.1		23.1	35.9
Copper(mg/kg)	20.6	42.5	59.9	62-340	11.9	20.5
Lead (mg/kg)	52.5	110	145	180-2400	30.2	38.6
Mercury (mg/kg)	0.13	0.35	0.33	0.5-1.9	0.13	0.27
Nickel (mg/kg)	21.1	28.5	37.1	42-230	13.5	21.38
Zinc (mg/kg)	81.2	121	211	N/A	45	81.1

**Willow SRC Leaves-only sites had noticeably higher levels of heavy metals *Normal Background Concentrations

10.3 Conclusions

The agreement between the results obtained from this project and those data reported in the Phyllis2 dataset is generally good, considering the limitations described above. Agreement for the *Miscanthus* and willow datasets was very good and whilst there were more discrepancies for the poplar and spruce SRF, the major differences noted can largely be explained by the fact that data for these species were reported as separate plant parts from this project, whilst the majority of the Phyllis2 data has to be assumed to be a mixture of plant parts. In general, the analysis of the trunks from this project indicated similar or lower concentrations of most elements that the Phyllis2 data, whilst the analysis of the tops indicated significantly higher concentrations. While it appears that the spruce tops contained lower levels of most trace and ash-forming elements than the Phyllis2 dataset, despite a higher ash content, much of this apparent discrepancy is due to the limited number of element analyses in the Phyllis2 database. In addition, most of the Phyllis2 data that are available are for "logging residues", which may be expected to correspond more closely to the tops samples from this study.

Although Phyllis2 is recognised as probably the biggest and most robust of all the publically-accessible biomass analysis databases, its use for this comparative study has highlighted the general lack of analysis data on biomass. The highest number of samples in a given dataset was 53 for *Miscanthus*, but for other species, sample numbers were often much lower.

For the soils, only a comparison of trace elements was available, but the results suggested that the sites selected for this project were in general uncontaminated and displayed relatively low levels of trace elements, which were lower than or in line with 'rural' settings as defined by the UK Soil and Herbage Pollutant Survey.

11 *Miscanthus* Pellets

11.1 Introduction

The focus of the majority of this project has been on the chemical characterisation of biomass feedstocks. Physical properties (e.g. bulk density) of biomass vary greatly and are largely dependent on the moisture content and particle size effects, as well as the inherent density of the biomass itself. As a result, these properties are often better assessed on a site/process specific basis. It was considered inappropriate to determine the physical properties of the raw biomasses sampled for this project, as the majority of samples were hand-sampled and the particle size provided to the laboratory for analysis would not necessarily be representative of that produced by a commercial harvesting system.

The primary reason for pelletising biomass for energy conversion is usually to improve its bulk/energy density and handleability, both during transport and during handling and storage. Bulk transport carriers, whether ships, trucks or rail wagons are, in general, designed to carry more dense materials such as grain, aggregates or coal. As such, the capacity limit per vehicle is most often set by the volume of biomass which can be accommodated, not the weight. Therefore, transport costs for biomass can be considered as roughly scalable with volumetric energy density. From a handleability and storage perspective, the range of physical forms of raw biomass are vast, from whole trunks, tops and branches, chipped products through to fine powders such as sawdust. The process of pelletising such a vast array of possible input forms is intended to result in a homogeneous, predictable product of consistent size, making handling and storage significantly easier to manage.

There is a cost associated with the pelletising process, which will include the necessary drying, grinding and pelletising itself, and this cost has to be balanced with the benefits of improved logistics, with the latter tending to dominate as transport distances increase. As such, most internationally traded biomass for energy tends to be in the form of pellets, whilst indigenous/ local sources are often traded in an unprocessed form. It is also worth noting that for non-EU imports, the pelletising process allows compliance with phytosanitary requirements to ensure that diseases are not spread through movement of plants or plant parts. Other benefits from pelletising material can include lower CAPEX (particularly for small scale users and when converting pulverised fuel combustion plants) and the application of standards which make it a consistent, predictable fuel.

In terms of changes to chemical properties, the relatively simple process of drying, size reduction and pelletising a biomass material might not be expected to have a significant effect on the majority of its chemical characteristics. The obvious exception to this is on the moisture content, and the resulting effect on all those parameters reported on an ‘as received’ basis, as well as Net CV. It is considered reasonably unlikely that the temperatures and pressures experienced in a pellet mill would be sufficient to alter other chemical characteristics (e.g. loss of volatile species) but it was considered worth investigation for this project, albeit very briefly. However, it is worth noting that various materials may be added to the biomass undergoing the pelleting process. Addition of steam to ‘condition’ the material is often undertaken to supply moisture for lubrication, the steam can also help liberate natural oils and, in some cases, results in partial gelatinization of starches. Deliberate use of solid additives during the pelletising process is also fairly common to improve pellet strength (binders), and to improve throughput and pellet die life (lubricants). Any use of additive will have the risk of impacting

on the final chemical characteristics of the pellet, depending on its nature. Contamination might also occur through unintended contact with other types of biomass species being processed in the pellet plant, or contamination from the pellet mill itself (wear products).

11.2 Methodology

Specific pelleting trials of the feedstocks sampled for this project were outside the scope of this work. It was originally hoped that a number of EON's pellet suppliers would be able to supply both raw and pelleted wood products, but unfortunately as all of EON's wood pellet supply was in the USA, importing of raw un-pelleted wood was not permitted for UK phytosanitary import restrictions. UK industrial wood pellet suppliers are relatively uncommon; several other large scale commercial wood pellet producers were approached, , but unfortunately none of them were able to commit to supplying the project with both raw and pelleted products. However, a UK supplier of *Miscanthus* pellets offered to take samples of the input raw material and the pellet at the same point in time and provide them to the project for analysis.

The pellet manufacturer provided the first batch of pellets and the raw (un-pelleted) chipped material in July 2015. Following the laboratory analysis performed at Uniper Technologies it soon became apparent something was wrong with the chemical composition. The pellet producer was contacted again for further samples to analyse. These second samples took a further month to arrive as the pellet producer had temporarily switched to cereal straw pellet production. The second round of pellets exhibited the similar chemical composition results as the first batch, so a meeting was held with the pellet producer to request information on the reasoning for additives and quantities being used. The pellet producer confirmed that their customer was aware of the additives being used, in this case caustic soda, to improve throughput of their pellet plant. A further request of *Miscanthus* material of both chipped raw and pelleted products was made, but without the caustic soda additive. The third and final set of *Miscanthus* samples was provided approximately 3 weeks later.

Where appropriate, the average value obtained from the *Miscanthus* samples generated in this project have also been plotted on the following graphs to provide an additional comparison with the raw input material to the pellet plant. It is unfortunate that no equivalent samples were obtained for wood pellet, but general conclusions can be drawn by comparing the average wood pellet chemical data provided by Uniper to the project with the average data from woody biomass from the project, as discussed in Section 12.

11.3 Results

The first batch of *Miscanthus* pellets and raw input material (3 replicate samples of each) was received and analysed, but it was immediately apparent that the chlorine and nitrogen level in the pellets was far higher than in the input material (see Figure 11-1 and Figure 11-2).

Figure 11-1: Chlorine content of fresh and pelletised *Miscanthus*

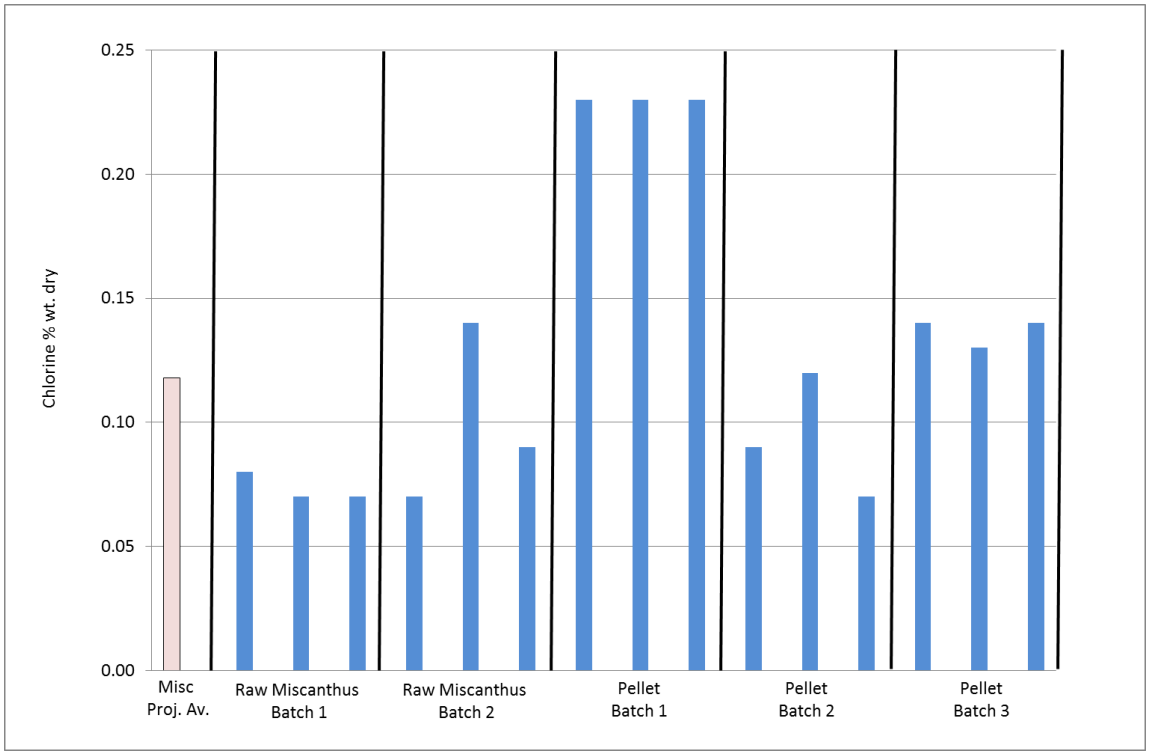
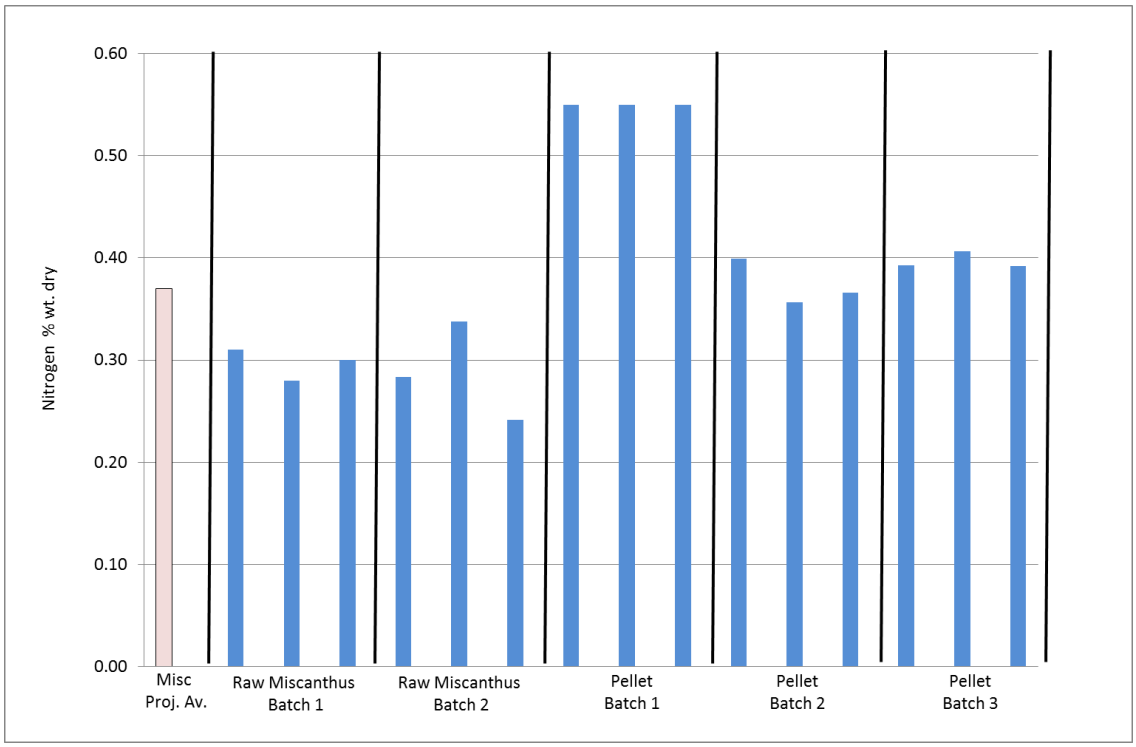
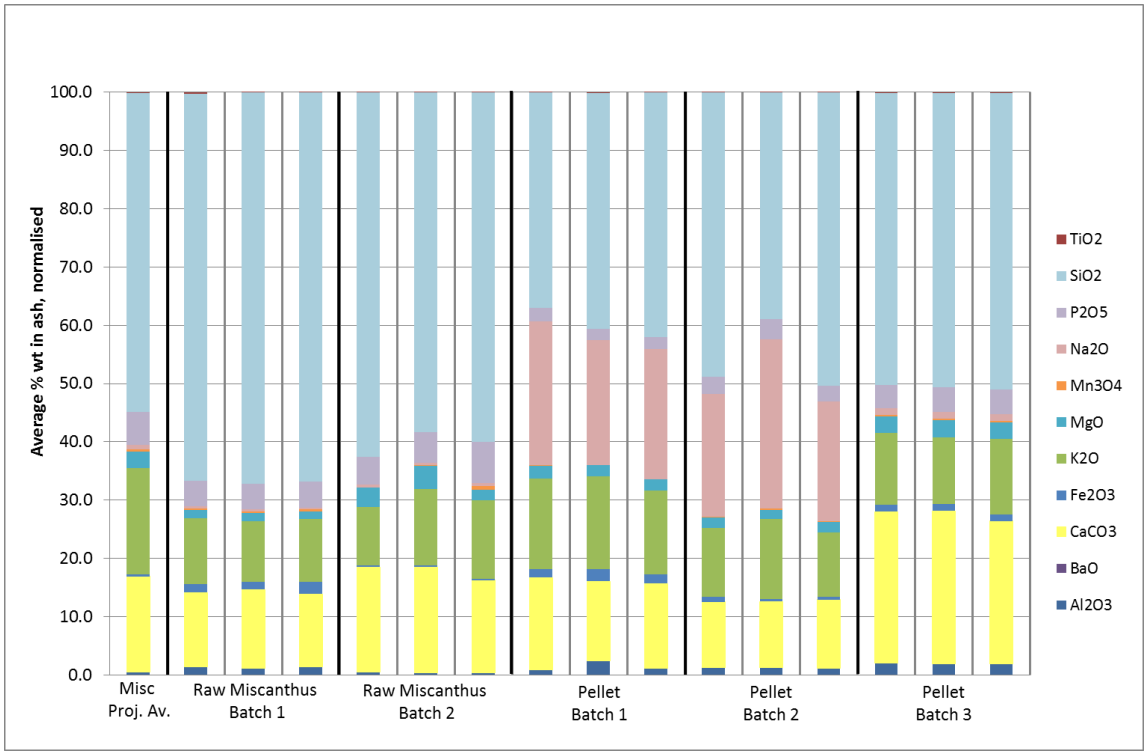


Figure 11-2: Nitrogen content of fresh and pelletised *Miscanthus*



The supplier could provide no explanation for this observation, and a second batch of pellets and input material (again 3 replicate samples) was provided. The chlorine and nitrogen levels on this occasion were closer for the raw and pelletised material, but when the ash composition data was received, a significant difference in the sodium content was apparent – see Figure 11-3.

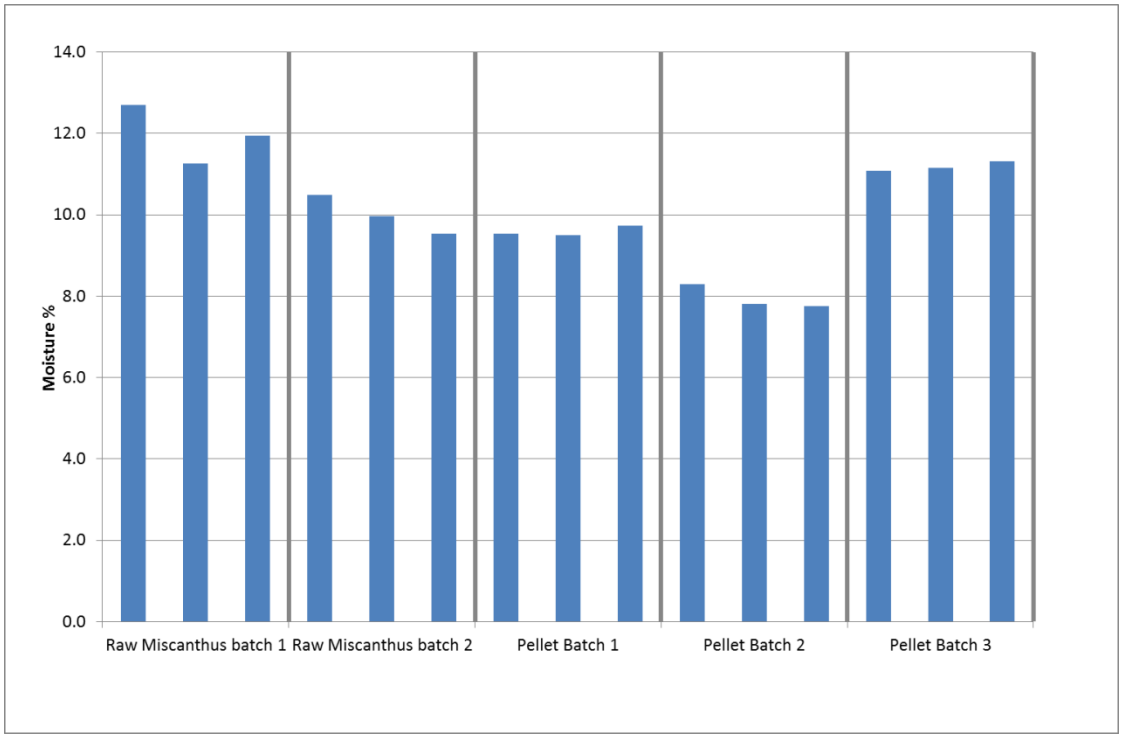
Figure 11-3: Normalised ash composition of fresh and pelletised *Miscanthus*



Looking back at the data from the first batch of rejected samples, it is clear that sodium was also higher in this batch. Further investigation with the supplier revealed that caustic soda is often added to pellets to improve die lubrication/ throughout, and hence overall lifespan of the pellet die. A third batch of pellets was requested specifically without caustic addition, although in this case no equivalent raw input material was received. However, it appears that the calcium content in these pellets is higher than in any of the other batches of material – which suggests that the caustic soda may have been replaced with limestone as an additive. The above incidents illustrate the difficulty of attempting to conduct a comparative sampling experiment whilst being reliant on, and having no direct control over, a commercial operation to provide samples.

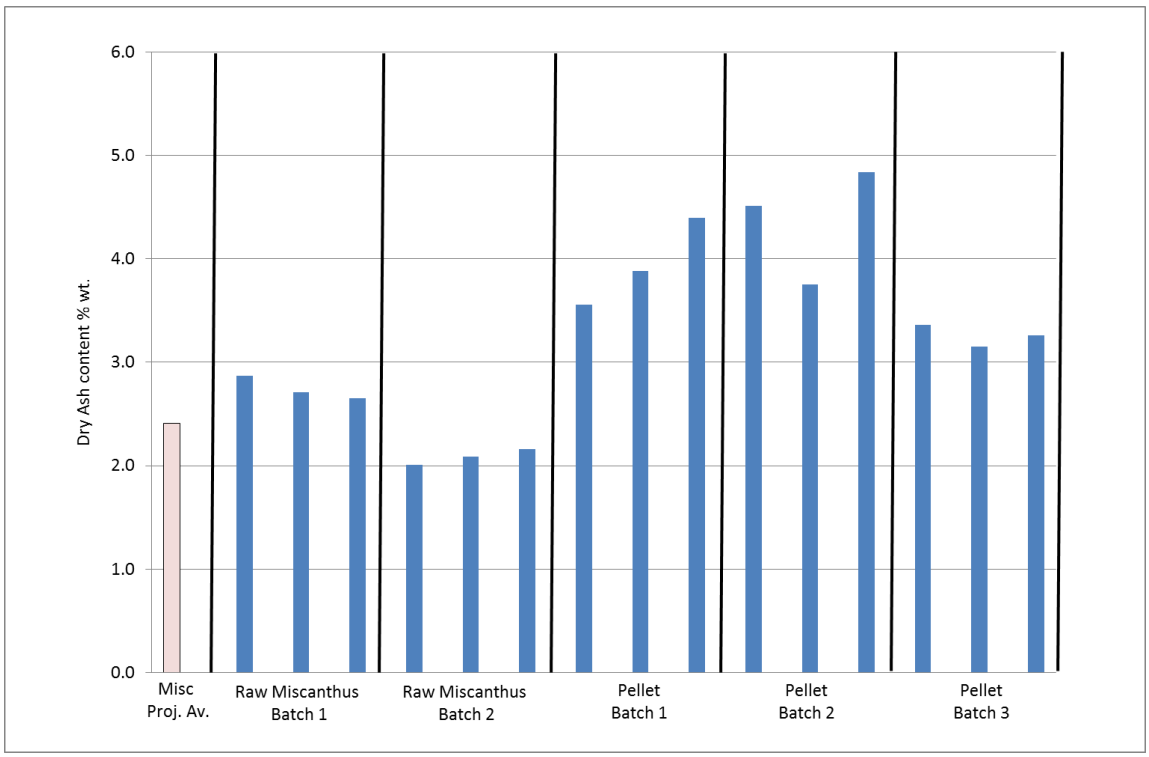
No statistical analyses were undertaken on the analysis data (as the use of additives makes it impossible to identify whether differences were down to the feedstock or additive) but in general the moisture levels of the raw and pelletised materials were similar; the raw material was sampled immediately pre-pelletising, and so will have been dried to a large extent already, with any additional drying of the pellets taking place during the pelletising itself – see Figure 11-4. In this chart, no comparison has been made with the average moisture content of the *Miscanthus* samples generated from this project as these were not pre-dried,

Figure 11-4: Moisture content of fresh and pelletised *Miscanthus*



Linked to the comments above regarding possible addition of caustic soda and limestone, the dry ash content of the pellets was consistently higher by between 0.5 and 1% than the raw input material – this probably being the result of the addition of these inorganic materials, see Figure 11-5.

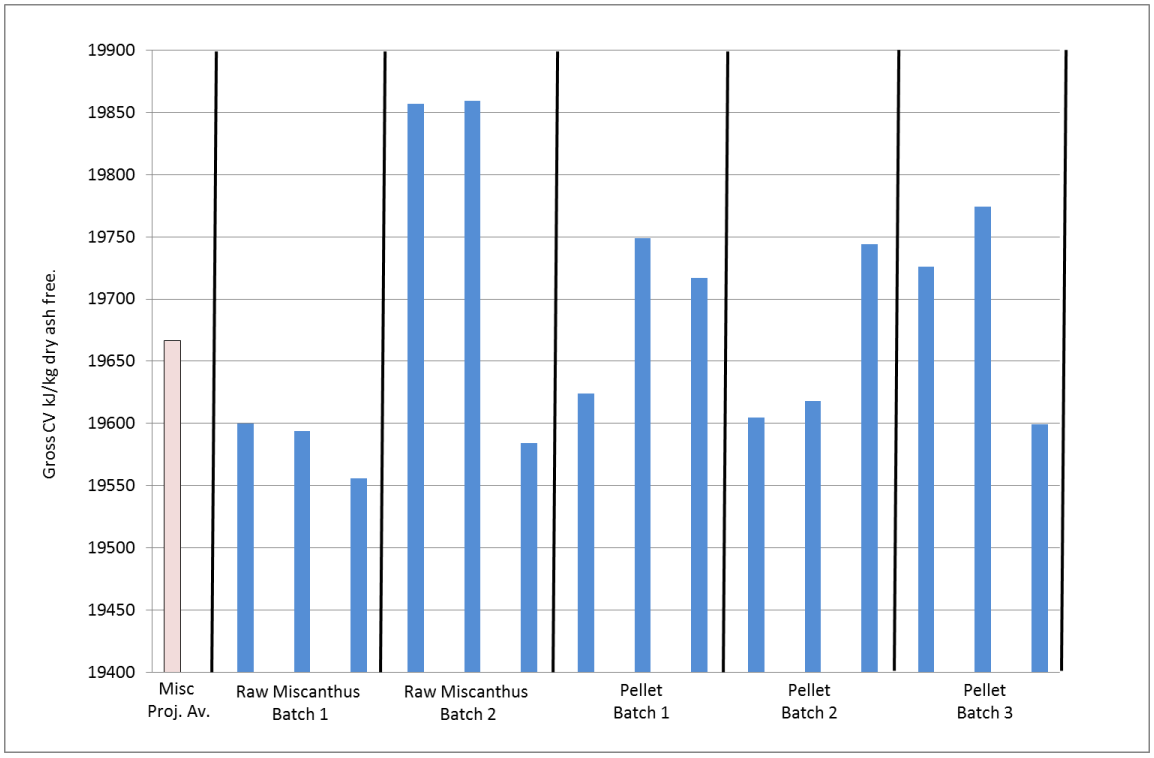
Figure 11-5: Dry ash content of fresh and pelletised *Miscanthus*



The dry ash free Gross CV of the raw and pelletised material shows some surprising variability between each of the three replicate samples, some of which was greater than the expected

experimental reproducibility, but there was no evidence of any significant change from raw to pelletised material (Figure 11-6).

Figure 11-6: Gross calorific value of fresh and pelletised *Miscanthus*



For dry chlorine content the unexplained contamination of the first batch of pellets resulted in a more than doubling of the concentration compared to the raw input material, see Figure 11-1. Although there is some variation between the three replicates for Batch 2, the average does not appear to change pre- and post-pelletisation. The Batch 3 pellets appear to show slightly elevated chlorine content compared to the raw Batch 1 and 2 input materials – this is unexplained.

In terms of ash compositional data (Figure 11-3), the major changes are in terms of the sodium (Batch 1 and 2 pellets) and calcium contents (Batch 3 pellets), due to the suspected use of inorganic additives in the process. Levels of other components were broadly unchanged. In terms of trace elements there are few general trends that can be drawn. High levels of variability were noted between each of three replicates in many of the batches of samples supplied, particularly for Ba, Zn, Cr, V, Sb and As. The variation between batches was almost always larger than any change from raw material to pelletised material making it difficult to draw firm conclusions. However, there are indications that the pelletised forms contain higher levels of elements such as Be, Co, Cr, Ni & V that might be related to contamination from metallic wear from the grinding process and pellet mill. Figure 11-7 to Figure 11-11 illustrate the behaviour of all the trace elements determined in the raw and pelletised materials.

Figure 11-7: Barium, copper and zinc content of fresh and pelletised *Miscanthus*

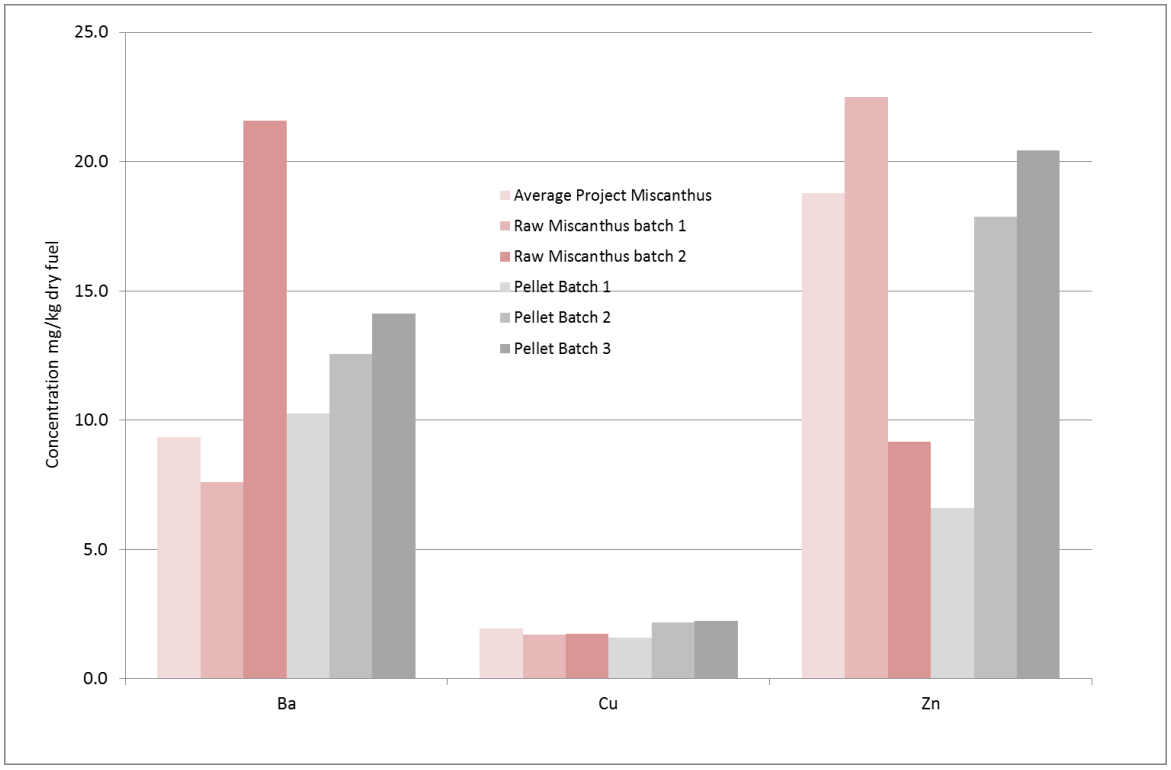


Figure 11-8: Chromium, nickel, vanadium and lead content of fresh and pelletised *Miscanthus*

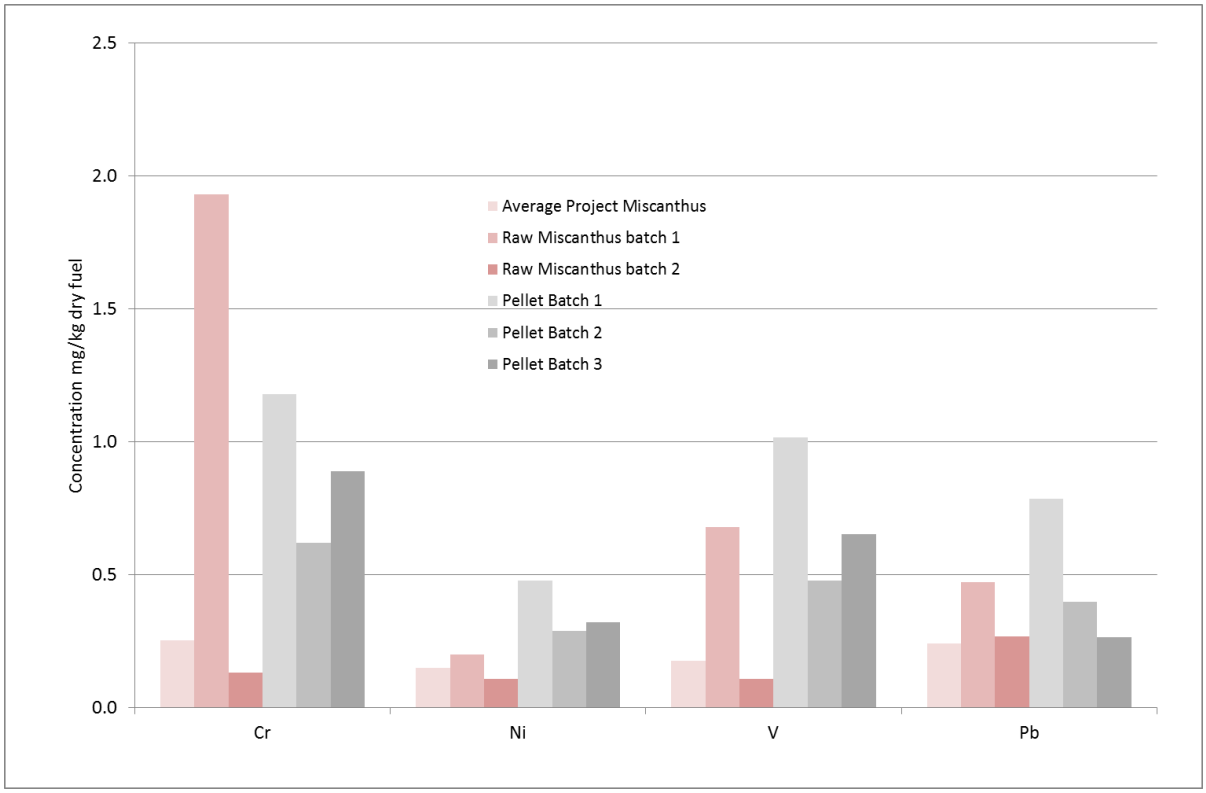


Figure 11-9: Beryllium, cobalt, molybdenum and antimony content of fresh and pelletised *Miscanthus*

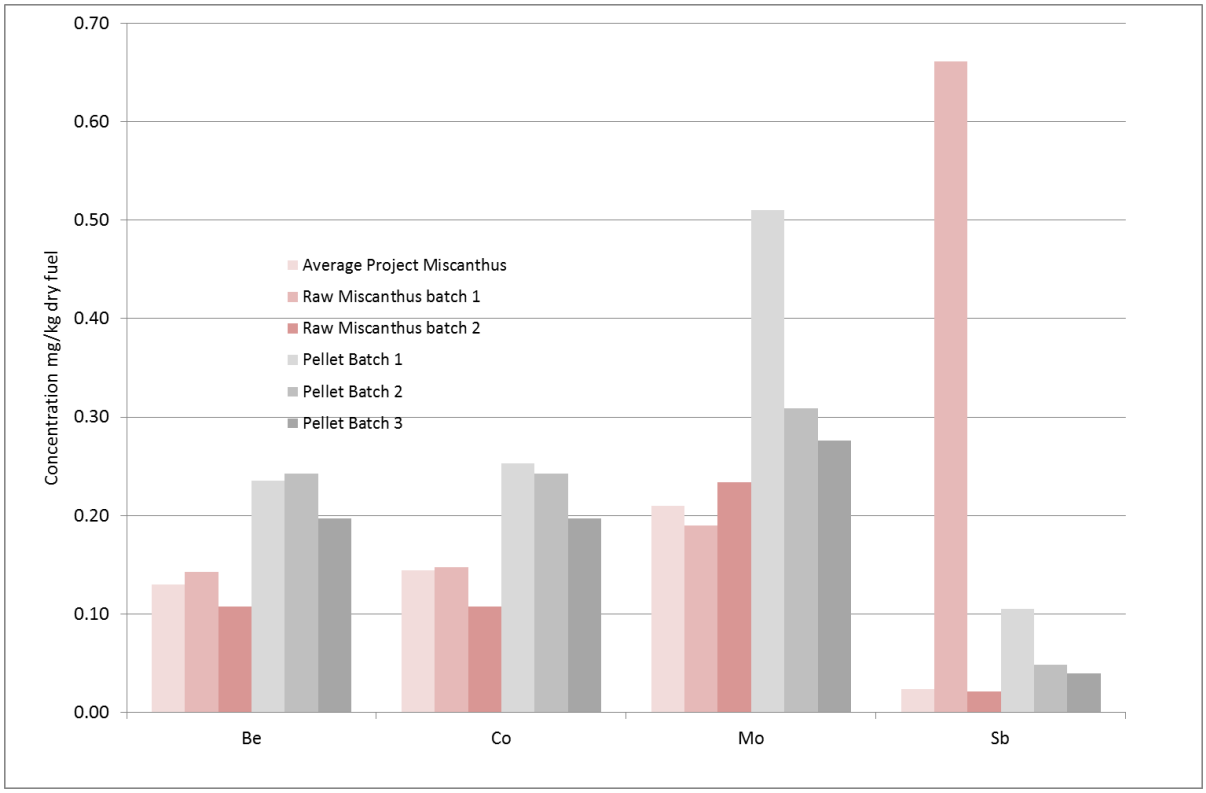


Figure 11-10: Arsenic, mercury, selenium and cadmium content of fresh and pelletised *Miscanthus*

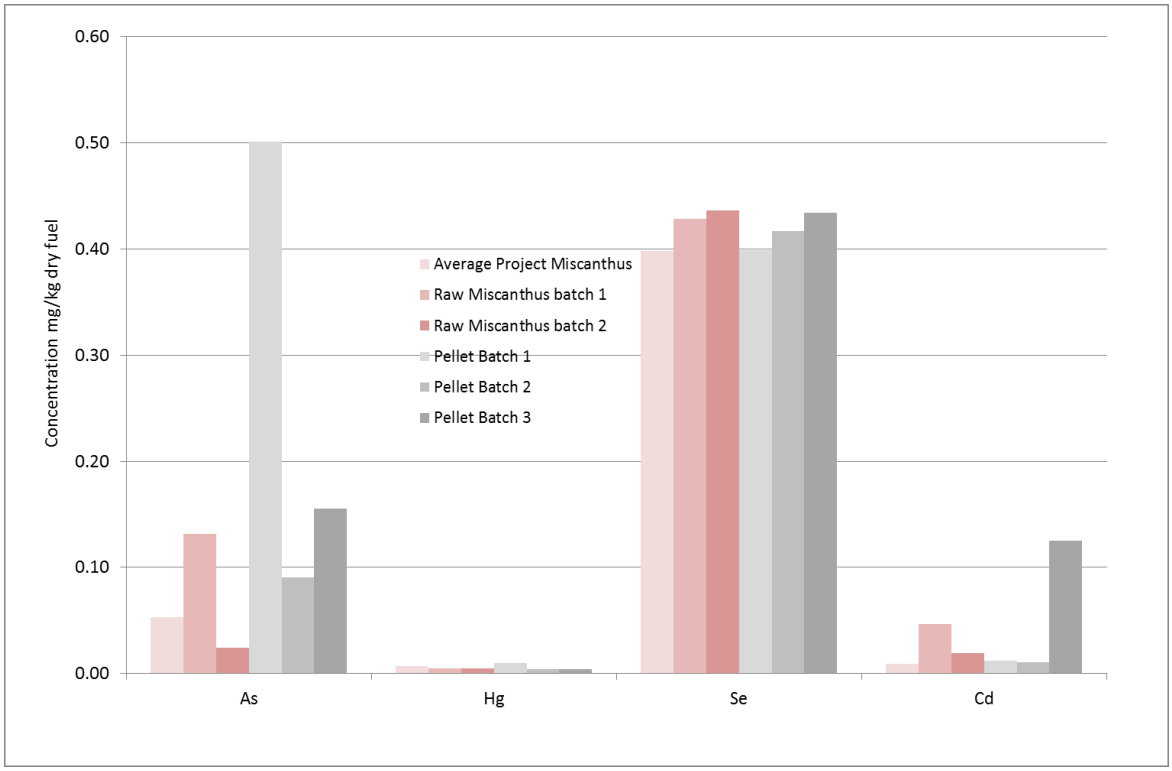
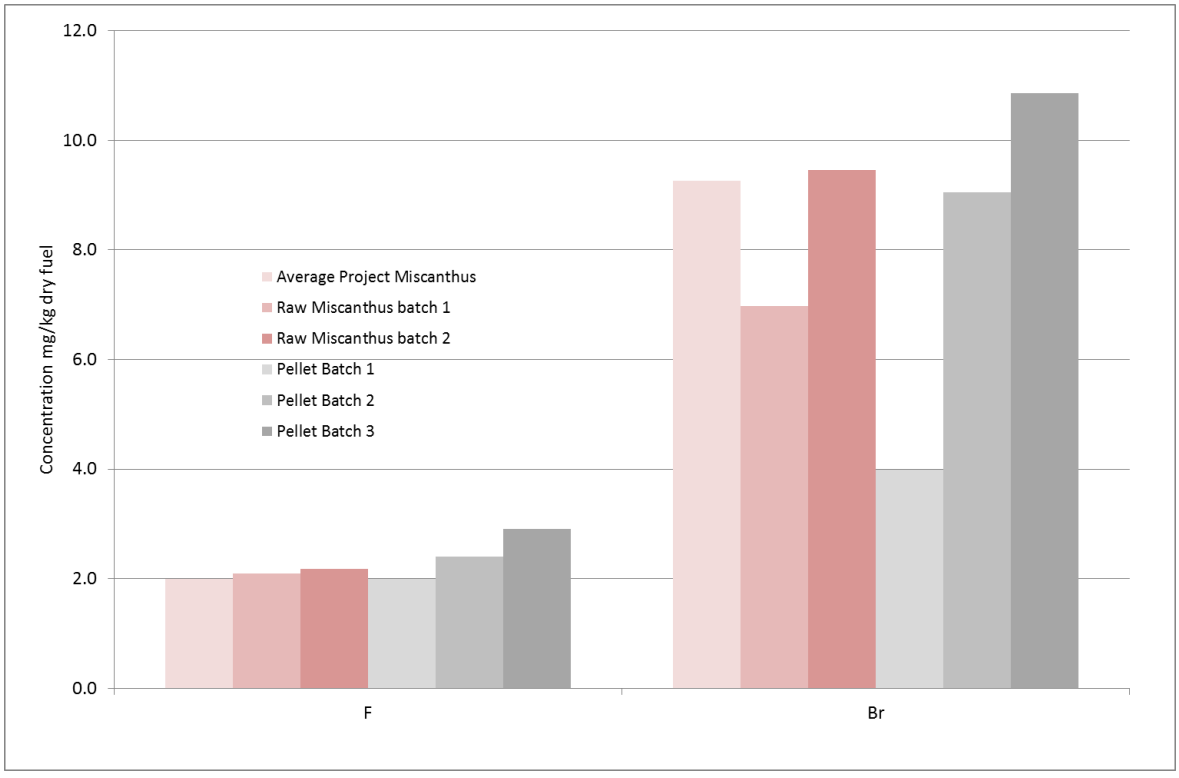


Figure 11-11: Fluorine and bromine content of fresh and pelletised *Miscanthus*



Section 12 discusses the historic wood pellet data provided by Uniper and compares this with the raw woody biomass samples taken during this project. It is evident that the wood pellets show signs of increased concentrations of certain elements such as Co, Cr, Mo, V, plus As, Sb, Pb and F compared to the raw biomass. Whilst it is recognised that the data sources for the raw and pelletised forms are completely unrelated, it suggests that there is at least some

scope for limited metallic contamination of the pellet form, which is presumably due to the grinding and pelletising process.

In terms of physical properties, the major change on pelletisation was bulk density. The raw *Miscanthus* was provided in dried, chopped form of approx. 50 mm lengths and was dusty with poor flow properties. It was shown to have a very low bulk density of 100-150 kg/m^3. The resulting pellets were approximately 6mm in diameter and 25 mm in length and had a bulk density of over 600 kg/m^3. The fines content of the pellets (<3.15 mm) was generally <2%, and the strength of the pellets, determined as 'durability' was determined to be >97%.

11.4 Summary

This exercise has clearly demonstrated the dramatic change in physical properties of biomass following pelletisation, but has yielded less information on the chemical characteristics. Ideally the sampling would have been undertaken during bespoke pelletising tests using the raw biomass species sampled for this project, but this was outside the scope of the project. The relevance of such bespoke and small-scale tests compared to real world commercial pellet mills is also questionable. The reliance on commercial pellet mills to provide samples will always carry the risk of the sampling being a second priority to the normal operation of the pellet plant, and this has probably resulted in many of the issues described above. The original project plan was for one set of samples to be taken for *Miscanthus* – it was only after the analysis of this initial batch was received that issues with the consistency between the raw and pelletised material could be identified and additional material requested. Time, feedstock availability (*Miscanthus* being a seasonal material) and budget constraints prevented further investigation of this.

The results do not provide conclusive evidence of significant chemical change during pelletisation, but the risk of contamination of the product appears to be relatively high, either from deliberate use of additives, from other materials or wear products from grinding process or the pellet mill itself. The results show that further communication between large scale end-users and pellet producers is important to ensure optimum and consistent pellet quality whilst maintaining pelleting performance. In particular, the downstream impacts of certain additives should be considered before they are used. For example, the caustic soda that was added to two batches of the pellets in this project (to improve throughput in the pellet plant) would pose severe slagging, fouling and corrosion risks to combustion plant.

12 Review of Historical Wood Pellet Data and Comparison to SRF Data

12.1 Introduction

Uniper has provided a substantial database of analysis results from imported wood pellets to the project to allow evaluation against the other feedstocks studied. The market for wood pellet has developed rapidly, to the extent that the UK is now one of the largest consumers in the world. The vast majority of wood pellet has been utilised in large scale utility furnaces, and although some of these have since closed (Ironbridge and Tilbury power stations), conversion of large generating units at Drax power station has meant that volumes have continued to grow. The majority of wood pellet so far has been imported from North America and Canada with additional supplies from Europe (including Portugal and Spain). Uniper's database consists of analysis of individual cargoes of wood pellet delivered over an 18 month period and includes over 200 samples, although not all parameters were determined on each sample. It should be noted that although the historic database covers the vast majority of parameters determined under the ETI study for the individual feedstocks, certain elements (e.g. bromine) were not determined in the wood pellets.

12.2 Pellet quality standards

At least two different quality schemes have been developed for wood pellets. The ENplus quality certification scheme has replaced numerous national standards and certifications with one uniform system based on the EN 14961-2 standard from 2011. This classifies pellets into three categories A1, A2 and B, which are aimed at the commercial and residential market. A1 is the premium pellet with the most stringent limits for trace elements and other species together with the most restrictions on feedstock types. Category B has higher limits for trace elements and other species and a wider variety of feedstocks are accepted including used wood (chemically untreated). A parallel scheme was developed by major wood pellet consumers (mainly European utilities) under the Initiative of Wood Pellet Buyers (IWPB). Three categories for industrial wood pellets were specified: I1, I2 and I3. Both the ENplus standards and the IWPB standards were combined under a single standard ISO 17225-2 in 2014. The pellets in the Uniper database were purchased against the I2 quality standard. Table 12-1 provides appropriate extracts from the ISO 17225-2:2014 for parameters relevant to those determined during this project. Where appropriate the limit values from the ISO standard are also included in the graphs presented in this Section. For non-woody pellets, ISO 17225 provides classes for individual parameters but no overall pellet standards, with product requirements generally agreed between the supplier and end user.

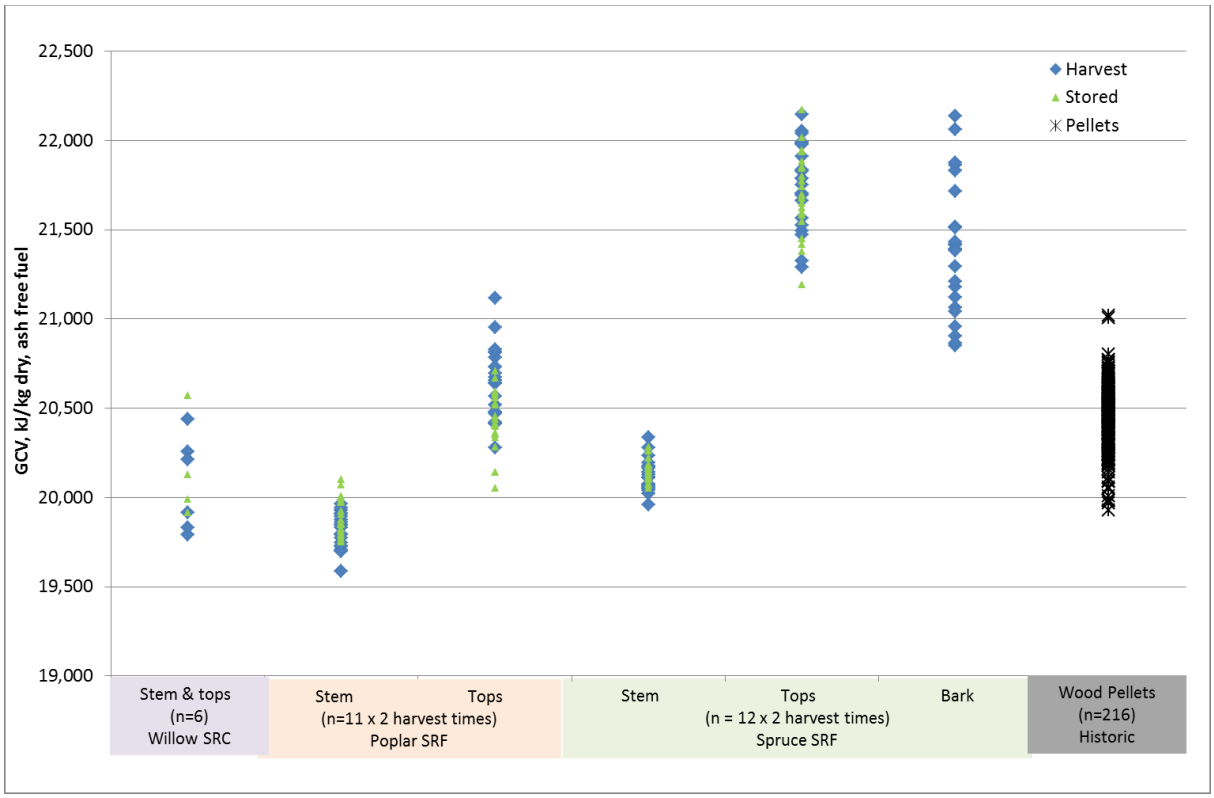
Table 12-1: Non-industrial (A/B) and Industrial (I) Pellet classes as defined in BS EN ISO 17725-2:2014

Property Class	Reference standard	A1	A2	B	I1	I2	I3
Origin/source (permitted feedstocks)	ISO 17225-1	Stemwood Chemically untreated wood residues	Whole trees without roots Stemwood Logging residues Chemically untreated wood residues	Forest, plantation, virgin wood By-products and residues from wood processing industry Chemically untreated wood residues	Forest, plantation, virgin wood Chemically untreated wood residues	Forest, plantation, virgin wood Chemically untreated wood residues	Forest, plantation, virgin wood By-products and residues from wood processing industry Chemically untreated wood residues
Moisture, %wt. (ar)	ISO 18134	≤10	≤10	≤10	≤10	≤10	≤10
Ash, %wt. (d)	ISO 18122	≤0.7	≤1.2	≤2.0	≤1.0	≤1.5	≤3.0
Mechanical Durability % (ar)	ISO 17831-1	≥97.5	≥97.5	≥96.5	≥97.5 ≤99.0	≥97.5 ≤99.0	≥97.5 ≤99.0
Fines, %wt. (ar)	ISO 18846	≤1.0	≤1.0	≤1.0	≤4.0	≤5.0	≤6.0
Additives, %wt. (ar)	-	≤2.0	≤2.0	≤2.0	≤3.0	≤3.0	≤3.0
	Type & amount to be stated						
Net CV, kJ/kg (ar)	ISO 18125	≥16,500	≥16,500	≥16,500	≥16,500	≥16,500	≥16,500
Bulk Density, kg/m^3 (ar)	ISO 17828	≥600	≥600	≥600	≥600	≥600	≥600
Nitrogen %wt. (d)	ISO 16948	≤0.3	≤0.5	≤1.0	≤0.3	≤0.3	≤0.6
Sulphur %wt. (d)	ISO 16994	≤0.04	≤0.05	≤0.05	≤0.05	≤0.05	≤0.05
Chlorine %wt. (d)	ISO 16994	≤0.02	≤0.02	≤0.03	≤0.03	≤0.05	≤0.1
Arsenic mg/kg (d)	ISO 16968	≤1	≤1	≤1	≤2	≤2	≤2
Cadmium mg/kg (d)	ISO 16968	≤0.5	≤0.5	≤0.5	≤1	≤1	≤1
Chromium mg/kg (d)	ISO 16968	≤10	≤10	≤10	≤15	≤15	≤15
Copper mg/kg (d)	ISO 16968	≤10	≤10	≤10	≤20	≤20	≤20
Lead mg/kg (d)	ISO 16968	≤10	≤10	≤10	≤20	≤20	≤20
Mercury mg/kg (d)	ISO 16968	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1
Nickel mg/kg (d)	ISO 16968	≤10	≤10	≤10	-	-	-
Zinc mg/kg (d)	ISO 16968	≤100	≤100	≤100	≤200	≤200	≤200

12.3 Results from pellet analysis

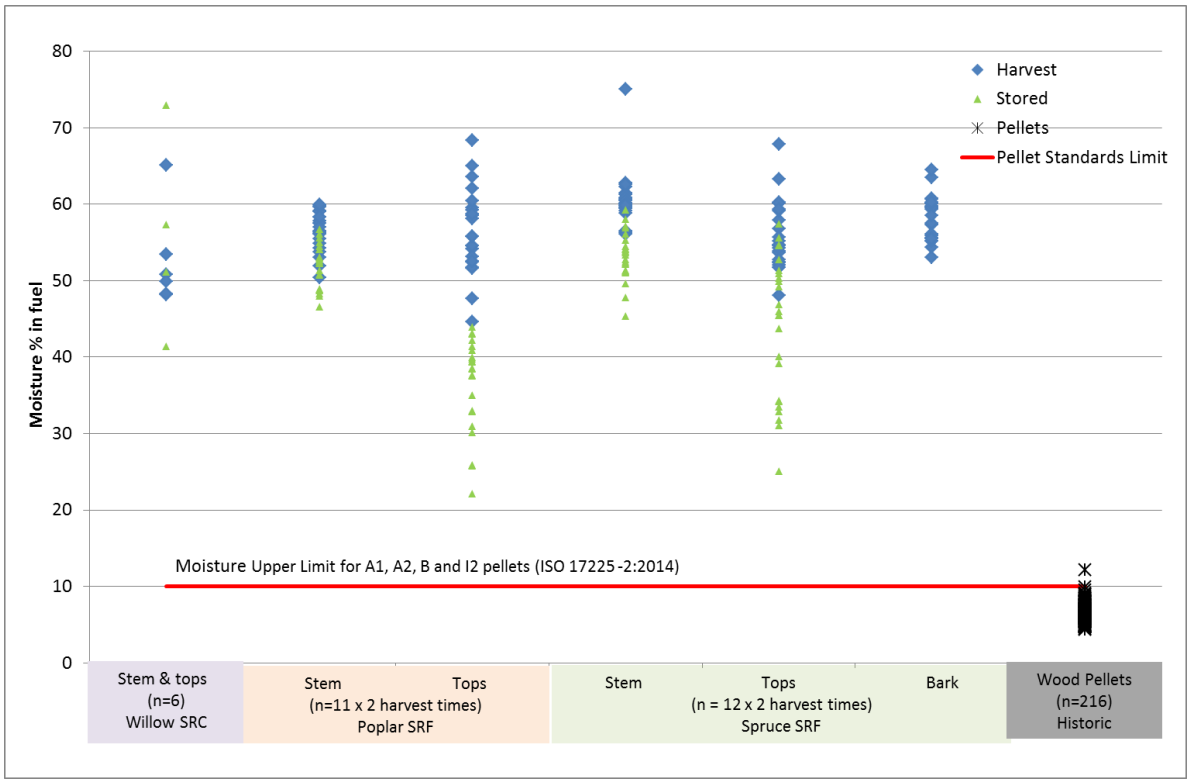
The results from the pellet analysis demonstrate an extremely consistent product considering the number of samples and the number of different suppliers. The DAF GCV shows a spread of approximately 1000 kJ/kg in DAF GCV, and comparing the historic wood pellet data with the woody biomass data from this project indicates comparable values, see Figure 12-1. Note that in Figures 12-1 to 12-10, 'Stem' of poplar SRF include the bark whereas the 'Stem' of spruce SRF do not include bark; for both feedstocks the 'Tops' include bark.

Figure 12-1: Gross calorific values (DAF) of woody project feedstocks in comparison to historical wood pellet data



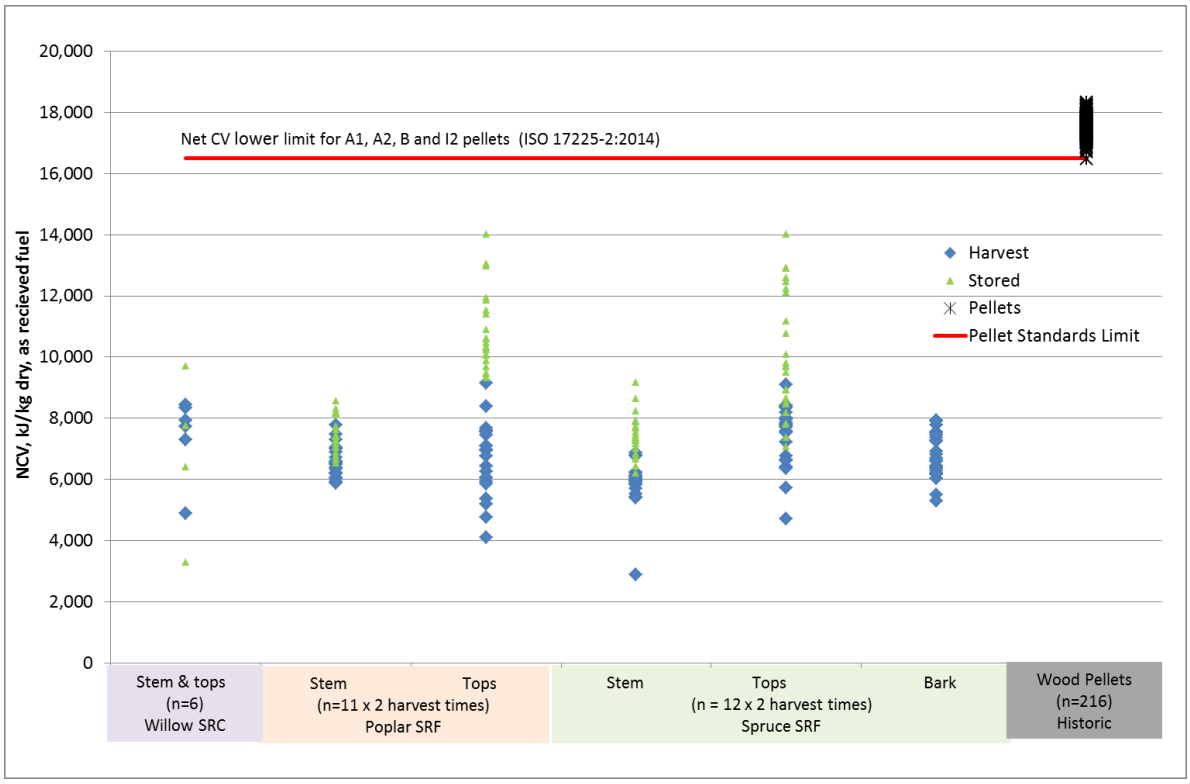
Some differences might be expected from the different (unidentified) wood species used to manufacture the wood pellet, and the use of both stem wood and branches/bark in the pellets would also be expected to result in a wider spread of DAF GCV than the individual plant parts. Having been though the pelletising process, the moisture content of the wood pellets is obviously much lower than any of the freshly harvested or stored woody biomass and apart from one or two samples is consistently below the 10% maximum moisture limit demanded by ISO 17225-2 for all the different pellet classifications, see Table 12-1.

Figure 12-2: Moisture content (ar) of woody project feedstocks in comparison to historical wood pellet data and pellet standard limits



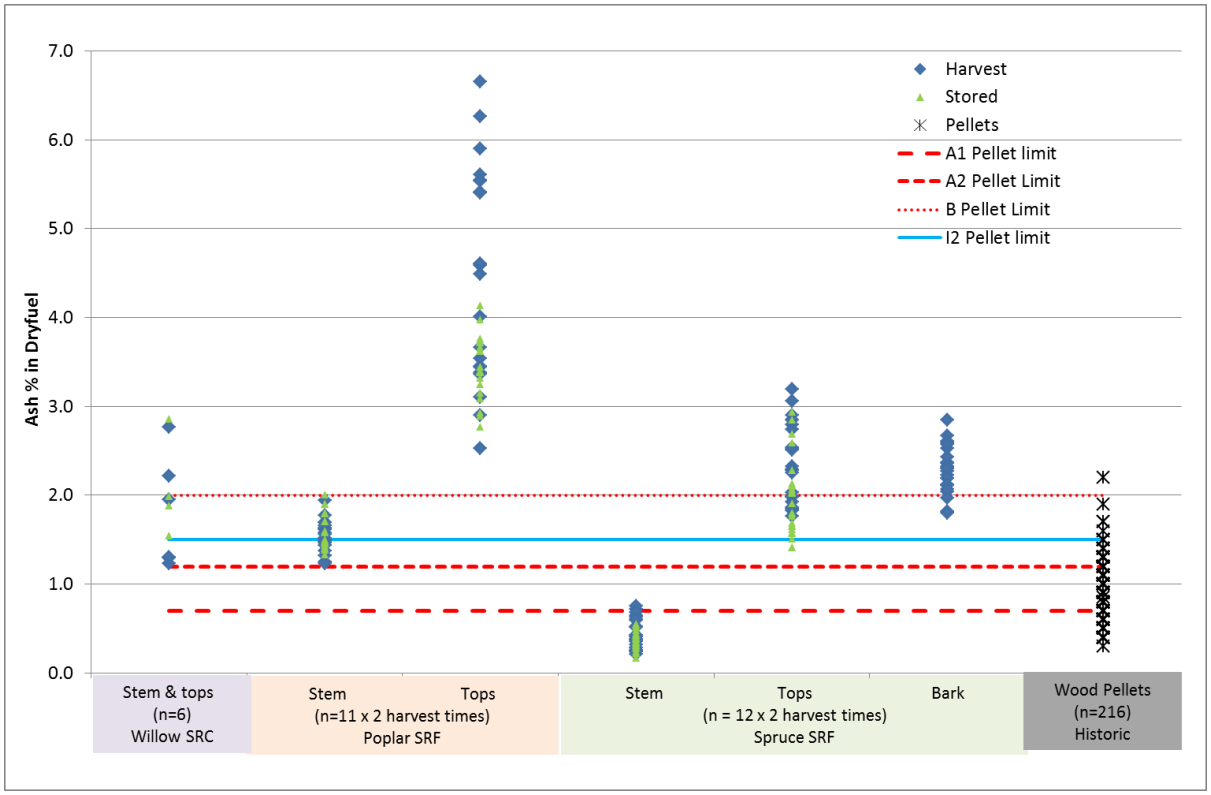
As noted previously, the Net CV is closely related to moisture (inversely) and again the data for the pellets is tightly clustered at or above the minimum limit demanded by ISO 17225-2 for all the pellet classifications at 16500kJ/kg, see Figure 12-3.

Figure 12-3: Net calorific values (ar) of woody project feedstocks in comparison to historical wood pellet data and pellet standard limits



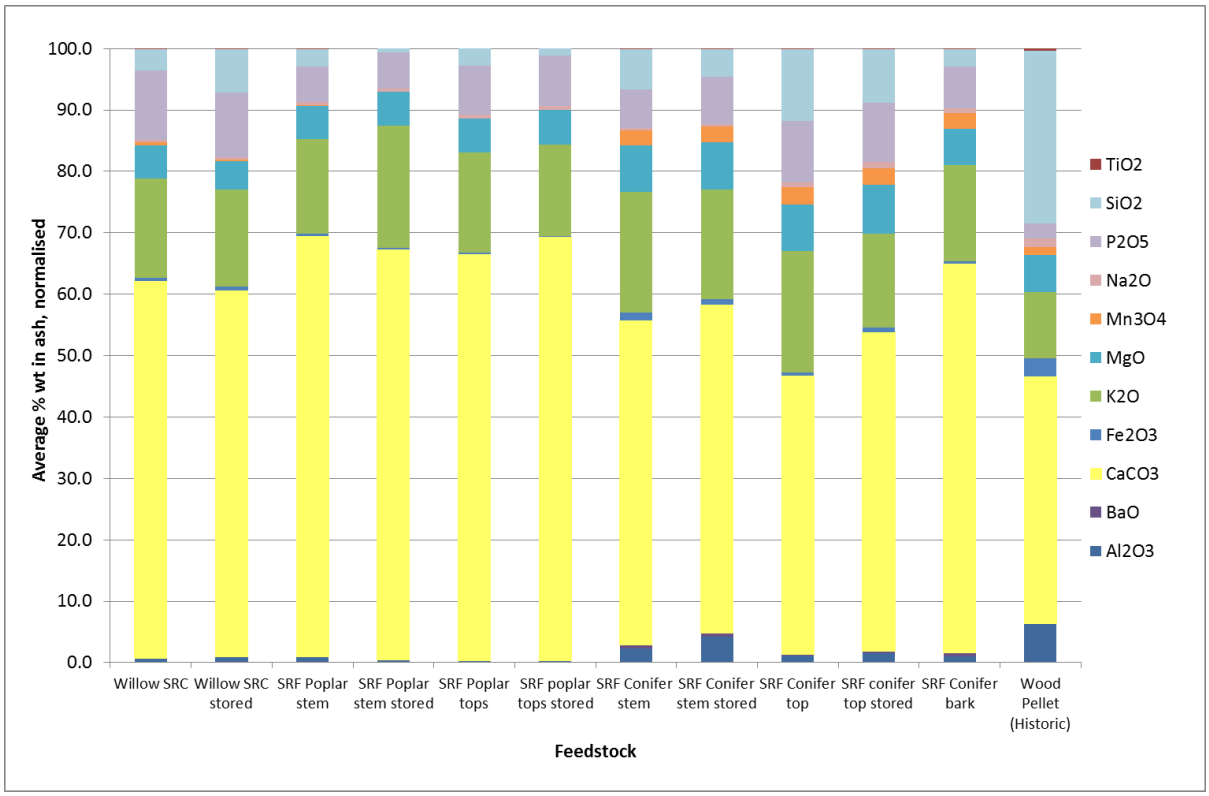
The chart for dry ash content (Figure 12-4) highlights the large differences between individual species and plant part and the range of data for the historic wood pellets, a portion of which exceeds the ISO 17225-2 standard for I2 pellets. For dry ash content, ISO 17225-2 quotes three different limits for pellet classifications A1, A2 and B, of which the latter is actually higher than that for the Industrial grade pellet I2.

Figure 12-4: Ash content (d) of woody project feedstocks in comparison to historical wood pellet data and pellet standard limits



Although the wood pellet would be expected to show a range of dry ash content reflecting the input materials (stem wood, branches and bark) a component of the ash would be expected to result from contamination with soil and dirt during harvest. All of the raw material for the wood pellets was harvested commercially, in comparison with the 'hand-sampling' of all the samples taken for this project. Further evidence of the possible contamination with soil and dirt can be seen from the ash composition analysis (Figure 12-5). If commercial conditions make it worthwhile to minimise wood contamination, this could be achieved relatively easily by adapting harvesting systems and using equipment such as 'feller-bunchers' that are commercially available to harvest and collect small diameter trees.

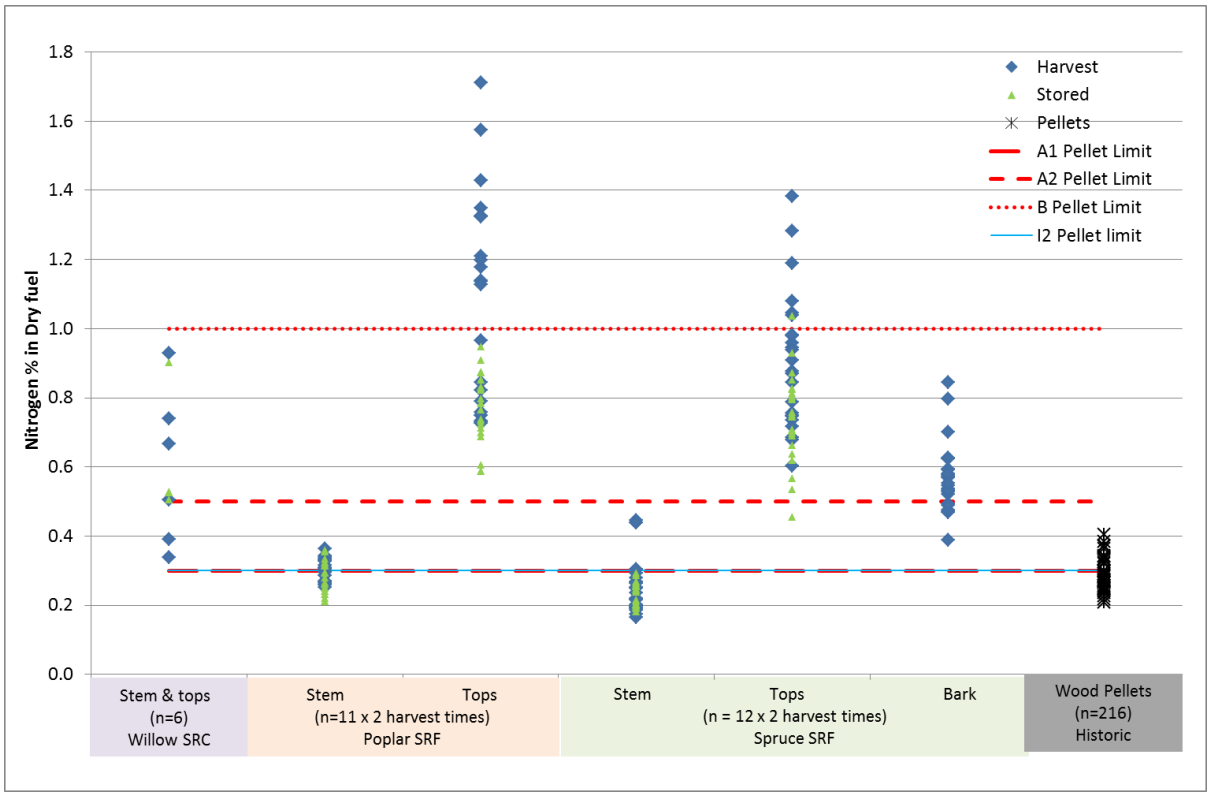
Figure 12-5: Normalised ash compositions of woody project feedstocks in comparison to historical wood pellet data



It is clear that the proportion of alumina and silica in the wood pellet ash is higher than any other feedstock investigated. Likewise, the proportion of calcium oxide in the wood pellet ash is the lowest. Although the raw wood species inputs into the pelletising process is unknown and therefore would have some influence on the differences in ash composition, high levels of aluminosilicate in woody biomass are relatively uncommon, and it is more likely to have been derived from the inclusion of free dirt (soil/stones etc.) during the harvesting of the wood. It is also interesting to note the slightly elevated iron and sodium contents in the wood pellet compared to the feedstocks. Whilst this could also be due to the differences in raw wood species that produced the pellets, it may be a consequence of contamination from the pellet grinding/milling process (iron) whilst the sodium could be the result of added caustic soda to improve die throughput (see Section 11.3). It is worth noting that the specifications for pellet in ISO 17225-2 allow for use of additives (up to 2 %wt in the commercial/residential pellets A1, A2 and B and up to 3 %wt in the industrial pellets I1, I2 and I3). However the standards note that if additives are used, then the 'type and amount should be stated'. Uniper were not made aware of any additives used in the wood pellets they sourced.

Of all the chemical limits in the I2 pellet specification, the one for nitrogen is probably the most stringent (at <0.3 %wt dry basis) and it is clear that a significant proportion of the wood pellets did not meet this standard (Figure 12-6).

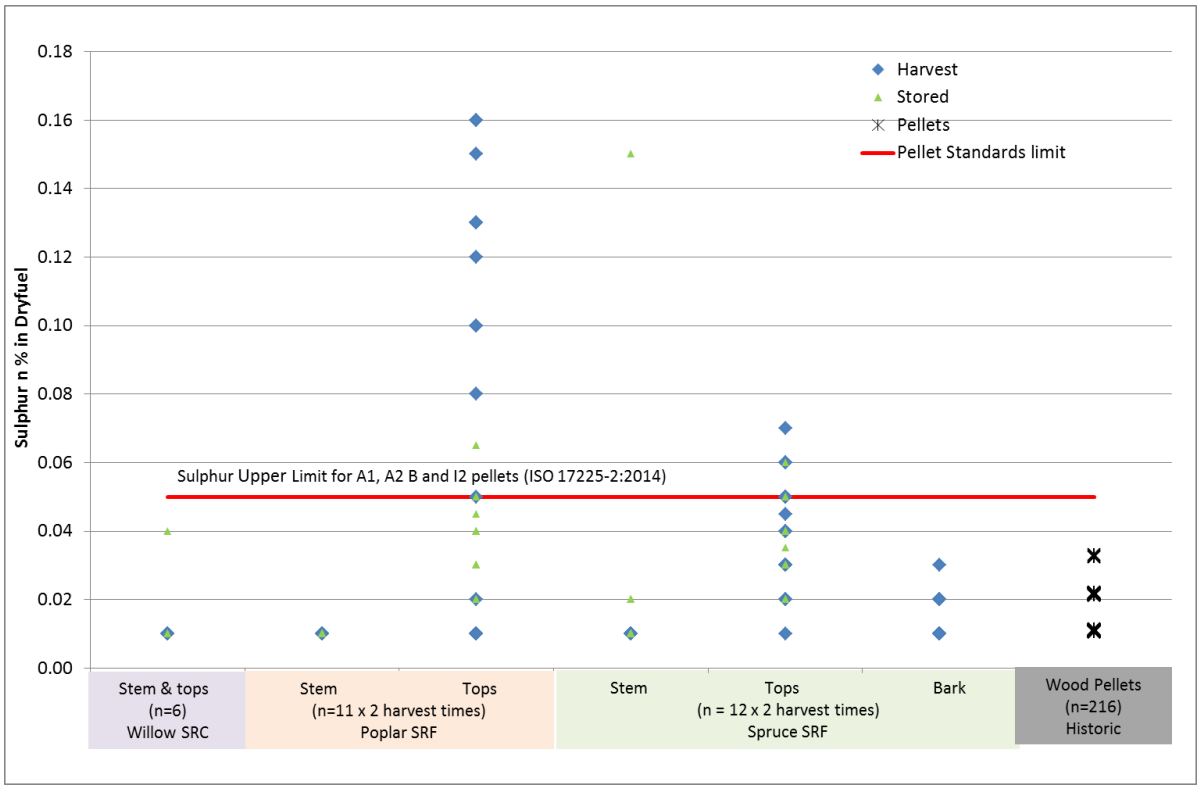
Figure 12-6: Nitrogen content (d) of woody project feedstocks in comparison to historical wood pellet data and pellet standard limits



ISO 17225-2 quotes three different dry nitrogen limits for commercial and domestic pellet classifications A1, A2 and B; it is interesting to note that these are all equivalent to, or higher than that for the Industrial grade pellet I2. In terms of the ETI samples, only the spruce SRF stem wood meets the strictest criteria (A1 and I2 pellet - <0.3% nitrogen (dry)) for most samples, with the spruce tops and bark exceeding it by some margin. Interestingly, many of the historic wood pellet samples do not meet the I2 nitrogen limit they were purchased against. While many of the poplar SRF trunk samples breached the tightest limits for nitrogen, overall levels were similar to those of the commercial wood pellet. As noted in earlier chapters, nitrogen in fuel is a key factor in determining NO_x emissions from the combustion system and industrial users in particular will demand lower values to minimize expenditure on flue gas clean-up systems.

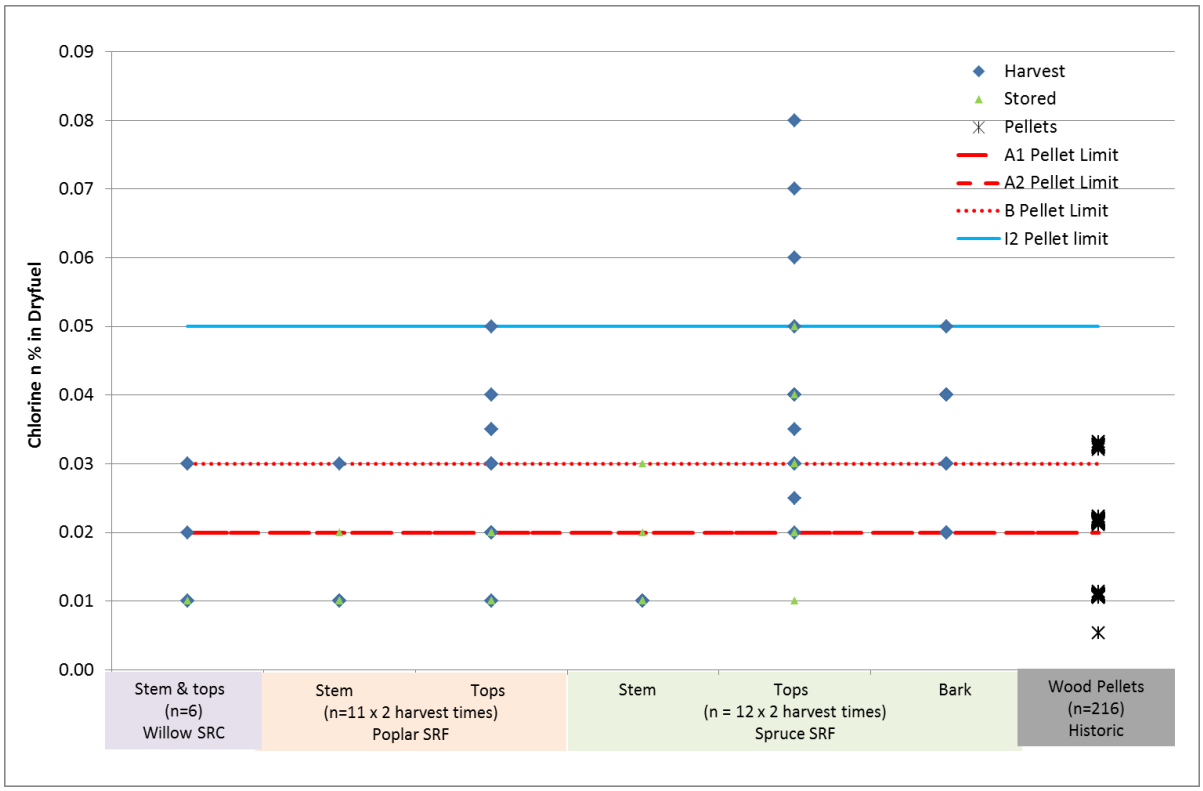
The limit of 0.05% sulphur (dry) for all the different pellet classifications is exceeded only by a few tops samples (Figure 12-7); it is worth noting that for the vast majority of trunk samples, sulphur was not detectable.

Figure 12-7: Sulphur content (d) of woody project feedstocks in comparison to historical wood pellet data and pellet standard limits



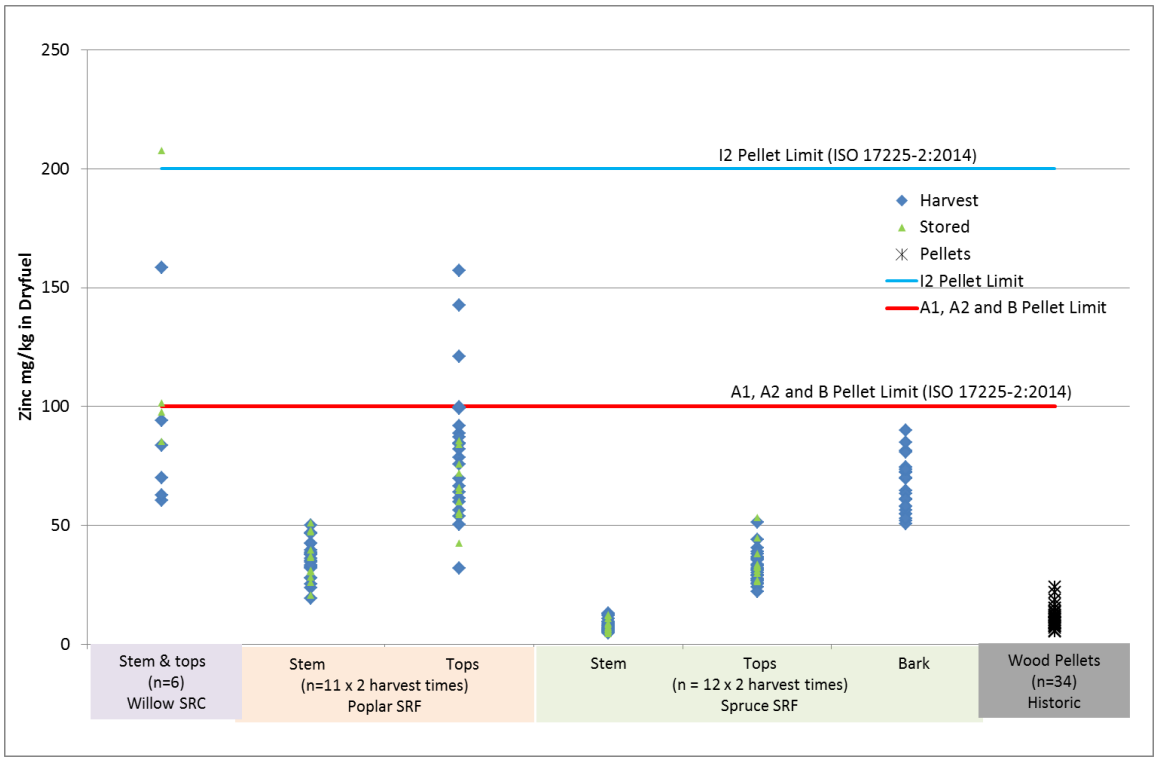
For chlorine, pellet classifications A1 and A2 have the same limit (0.02% (dry), the B pellet has a limit of 0.03% (dry) whilst the I2 pellet has a limit of 0.05% (dry). Similar to the limits for nitrogen, the lowest limits for chlorine are breached (albeit some only occasionally) by all the different plant parts, suggesting that these criteria may be a challenge to pellet producers. In addition, it should be recalled that sulphur and chlorine were found at significantly higher levels in the leaves, meaning that any contamination could significantly affect chlorine levels in the final product – as previously discussed, the sulphur and chlorine levels in the material from the second harvest decreased after storage, presumably due to the loss of the leaves. As a result, more of the stored poplar SRF top samples complied with the pellet standard sulphur limits.

Figure 12-8: Chlorine content (d) of woody project feedstocks in comparison to historical wood pellet data and pellet standard limits



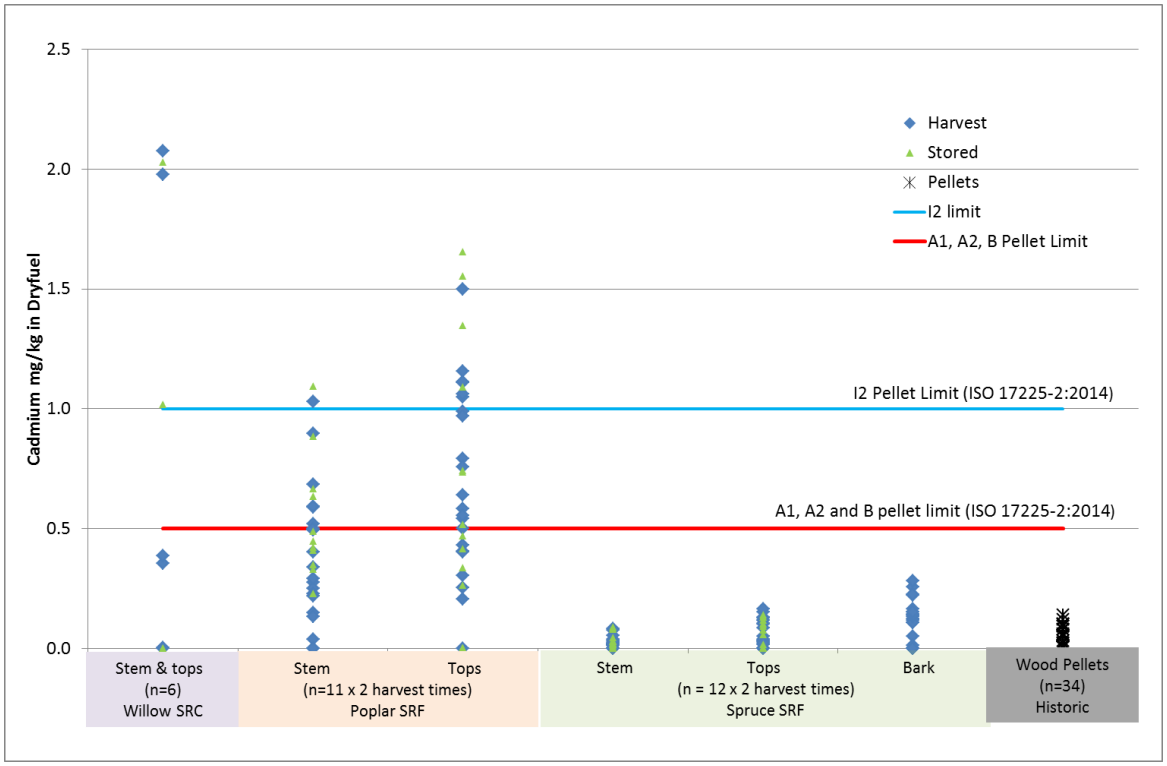
In terms of content of trace elements, the A1, A2, B and I2 specifications give limits for the species As, Cd, Cr, Cu, Pb, Hg, Zn, nickel is additionally included in the specifications for the specifications A1, A2 and B. For the majority of elements, all of the feedstocks and pellet analyses were comfortably lower than the specified limit with the exception of copper and zinc, where the lower limits specified for classifications A1, A2 and B were exceeded by a few poplar SRF top and willow SRC samples – see Figure 12-9.

Figure 12-9: Zinc content (d) of woody project feedstocks in comparison to historical wood pellet data and pellet standard limits



For cadmium however the limit of 0.5mg/kg dry fuel for pellet types A1, A2 and B proves to be very challenging for a good proportion of the poplar SRF dataset (both trunk and tops) and some willow SRC samples, although it is comfortably achieved for all the spruce SRF plant parts – see Figure 12-10.

Figure 12-10 Cadmium content (d) of woody project feedstocks in comparison to historical wood pellet data and pellet standard limits



For many trace element species including Ba, Be, Cu, Ni the concentrations in the wood pellets were generally very similar to those seen in the feedstock trunks and tops. However for certain species, including Cr, Co, Mo, V, As, F and to a lesser extent Sb and Pb, the concentrations in the wood pellets were more scattered, with a significant quantity of the wood pellet samples at higher concentrations than in the feedstocks. Conversely, levels of Zn, Cd and Hg were in fact notably lower in the wood pellets than in the feedstocks. These differences could simply be due to the differing feedstocks used for the pellet manufacture, but the increased concentrations of several metals associated with steel might suggest the possibility of slight contamination of the pellets from the grinding and pelletising media, this could also be due to inclusion of soil and stones during harvesting. Although the dataset used for comparison of raw *Miscanthus* and pelletised *Miscanthus* was very small (Section 11), similar increases in at least some of the above elements (including Be, Co, Cr, Ni & V) were noted in the pellets compared to the feedstock which might re-inforce the evidence for metallic contamination.

12.4 Physical properties of pellets

In terms of physical properties, experience has shown that wood pellets have the potential to become degraded and produce large quantities of dust and fines. This results in problems with handleability, as well as health and safety concerns. All of the historic wood pellet samples were analysed for durability and fines content, whilst the bulk density of a smaller selection was also determined. The durability test is designed to assess the ability of a pellet to withstand destructive loads and force during handling, and is determined by measuring the percentage of pellets that survive a tumble test and are retained on a 3.15 mm sieve. The average durability of the wood pellets was 98.4% against a minimum in the ISO 17225-2:2014 I2 standard of 97% and the average fines (material <3.15 mm) was 2.14% against a limit in the standard of <5%. It should be noted that the limit values for fines are considerably more stringent at <1% for pellet classes A1, A2 and B. Experience has shown that any contact with moisture results in rapid degradation of wood pellets and certain cargoes, even when kept dry, can contain significant quantities of fines. The average bulk density of the wood pellets was 680 kg/m^3 against a minimum in the ISO 17225-2:2014 standard for all the pellet classes of 600 kg/m^3

12.5 Summary

In summary, the analysis data for the wood pellets highlights an extremely consistent and homogenous fuel source, given the multiple suppliers and sources used. For the majority of parameters determined, the wood pellet datasets were tightly clustered compared to the spread seen for the raw feedstocks analysed for this project. The pellet quality criteria which appear to be most challenging are for dry nitrogen and chlorine content where the strictest limits were exceeded by a good portion of the feedstock data. A reasonable portion of the wood pellet samples breached the I2 limit for nitrogen of 0.3% (dry). The strictest dry ash limits in the various pellet classes are also challenging, with the spruce SRF trunk material being the only plant part to consistently meet the lowest ash content limit for A1 pellets of 0.7% (dry). Contamination with soil and dirt during commercial harvesting must also be expected to contribute to overall ash content. In terms of trace elements, the limit for cadmium is the most challenging at 0.5mg/kg dry fuel for pellet types A1, A2 and B and this is exceeded by a proportion of the poplar SRF dataset (both trunk and tops) and some willow SRC samples, although it is comfortably achieved for all the spruce SRF plant parts. In addition for copper and zinc, the lower limits specified for classifications A1, A2 and B were exceeded by a few

poplar SRF top and willow SRC samples. None of the other trace element limits proved to be an issue. Certain trace elements appeared at higher concentrations in the pellets compared to the raw feedstocks and it is suspected that this could partly be due to contamination from the grinding and pelletising plant, but inclusion of soil and dirt may also be responsible.

13 Bioenergy Feedstock Production Costs

This section addresses the requirement to *identify farm gate poplar SRF prices and production costs (where possible) for use by the techno-economic assessment of biomass pre-treatment technologies project*. In subsequent discussions this was refined to be figures on typical costings and prices for fuels collected from the various management companies, where they were prepared to supply them, but that detailed analysis of practice at individual sites would not be included.

The cost figures in Table 13-1 were collected from relevant management companies as representative costs for the establishment, management and harvesting of their crops, together with typical prices for the fuel produced. These costs should be regarded as indicative only and compared with caution, as they will rely on different assumptions and include different potential additional costs, such as rabbit fencing, tree guards or replacing failed plants.

Table 13-1: Costs for the production of bioenergy crops

Crop	Typical yield odt/ha/a	Ground preparation /ha	Planting /ha	Planting material /ha	Total establishment cost /ha	Crop management /ha	Harvesting (inc. baling, stacking)	Harvesting per odt	Crop cost quoted ex farm
Miscanthus	12.5				£1,102	£90	£75 ha^{-1} + £13.50/t (@16% MC)	£22 odt^{-1} @ 12.5odt ha^{-1}	£62/t Baled, <16% MC ≈£74 odt^{-1}
Willow SRC	7	£199	£275	£950	£1,424	£223	£370-£380 ha^{-1} +£135 $hour^{-1}$	£29 odt^{-1} @ 7odt ha^{-1} a^{-1}	£37 odt^{-1} Chips or billets
Poplar SRC	n/a	£145-£150	£50-£75	£770	£965-£995	£70+cutback	NCA*		NCA*
Poplar SRF	2.1 (trunk) + 0.3 (tops)	£145-£150	£50-£75	£770	£965-£995	£70+pruning	£10-£11m^{-3} + £6m^{-3} Stacked roundwood @ 0.36 odt m^{-3} basic density	£67-£71 odt^{-1}	≥£18 m^{-3} ≈£75odt^{-1}
Spruce SRF	0.8 (trunk) + 0.4 (tops)	£500-£700	£175-£200	£500-£600	£1,175-£1,500	£210-£280	£19 m^{-3} (£8-£35 m^{-3}) Stacked roundwood @ 0.35 odt m^{--3} basic density	£81 odt^{-1} (£34-£150 odt^{-1})	NCA*

*Not commercially available

For some crops these costs are estimates as they do not represent current practice. Although Sitka spruce is a widely planted commercial forestry crop, it is not currently managed as Short Rotation Forest (SRF). Consequently, the cost of commercial harvesting at around 15 years is not clear. The harvesting equipment used for mature trees would be inefficient at this small tree size. In the UK, there are currently very few of the feller-bunchers that would be more suitable for this task and which might moderate costs, though they are available and used in other countries, and there have not been studies into the costs of using them on this crop.

The crops studied within this project are at different stages of commercial maturity for large-scale energy conversion - across the UK as a whole there is greatest experience in growing willow SRC, followed by *Miscanthus*, then poplar and finally spruce SRF for this market. Production and possibly also establishment costs may be expected to fall to a different extent upon further commercialisation of some of the crops owing to refinement or simplification of techniques and method/equipment development. These would be dependent in part on acceptable fuelwood /chip specification.

Site can have a considerable impact on establishment, management and harvesting costs. In particular the forestry type crops (such as SRF) may be expected to be planted on a more diverse range of sites than the more agricultural type crops. This will therefore have an impact on the range of establishment, management and harvesting costs. In some cases we have been given a range of figures to help reflect the variability in costs; in other cases we have been given typical, representative costs.

Establishment costs appear to range from slightly less than £1,000 per hectare (ha) to £1,500 ha^{-1}. It can be seen that the top end of the range is for establishing Sitka spruce and corresponds to difficult sites. It therefore cannot be compared directly with establishment of other crops on agricultural sites. It also includes components within both the planting and planting material costs for the replacement of trees that have died shortly after planting (beating up). The filling of gaps in the crop is important for good yield for all the crops and this may not be included in some of the other estimates.

In all cases a certain amount of weed control is assumed within the estimate of costs for crop management, however this it typically only for the first year or two, and in some cases prior to planting. The allowance for weed control varied significantly between different companies.

For SRC crops, an initial (pre-commercial) cutback is required a year after planting, the cost of which has been included, where relevant, in the crop management figures. In the case of *Miscanthus,* it is envisaged that the first two annual crops will be either left standing or require mowing, but will not be saleable.

The harvesting costs include baling or stacking where relevant, but again it is likely that the costs given will vary somewhat in exactly what is included and what is not. The form of the end product varies between crops, and this will be reflected in harvesting costs, while further processing to meet fuel specification will be required in most cases. The *Miscanthus* costs are to produce Hesston bales of around 600 kg, at <16% moisture content; the willow SRC costs are to produce chips or billets, while spruce SRF and poplar SRF harvesting costs are to produce solid roundwood, excluding branches and tops. As mentioned above, the harvesting costs for spruce SRF are estimates as this is not currently a commercial activity and would most efficiently be performed using equipment not currently widely available within the UK.

Although they cannot be directly compared in detail for the reasons given above, the harvesting costs per ha have been converted to cost per oven dry tonne (odt) of biomass fuel, to assist comparison. It must also be remembered that this conversion depends directly on yield. The yield assumed has been given in the table. Not only does the harvesting cost per odt increase with lower yield, the total revenue from the crop decreases.

Similarly, to assist comparison, where it was not given in this form, the prices of the produced biomass have also been converted to £ odt^{-1}. There are of course assumptions built into these conversions as moisture content and/or bulk density may vary, so these figures must also be treated with some caution. However, there appears to be some fairly significant differences which may in part be due to feedstock properties, but also possibly historical reasons where contracts were established a significant time ago. This is the case for the SRC willow, as some of the contracts are 10 years old and, although they incorporate some form of index linking, they still reflect costs that may no longer be current. More recently negotiated prices would be likely to be significantly higher. It should be noted that a number of SRC sites (both willow and poplar) have recently been removed due to the loss of contracts.

14 General Discussion

14.1 Project design

In this project, five feedstocks were included: *Miscanthus,* willow short rotation coppice (SRC), poplar SRC, poplar grown as short rotation forests (SRF), and spruce SRF, with poplar and Sitka spruce selected to represent broadleaved and coniferous biomass crops respectively. Prior to sampling, suitable sites were selected on the basis of their soil type and climate zone, based on GIS data. The databases upon which the soil designations were based were from the National Soil Map of Scotland from the James Hutton Institute, and the National Soil Map of England and Wales from The National Soil Resources Institute, converted by the Forestry Commission to the FC classification system. As well as collecting feedstock and soil samples for each site, provenance data (e.g. management practices) were also gathered.

14.1.1 Feedstock availability

The first complication in the completion of the study design was the feedstock availability. Current UK bioenergy market conditions do not necessarily promote the production of all of the feedstocks included in this project. As a result, during site selection both growers and suppliers advised that certain sites would only be available for a limited period of time, because end user contracts had expired and were not being replaced. Since the start of the project two large dedicated energy supply contracts, for willow SRC and *Miscanthus*, have come to an end. Consequently, finding sites that could be sampled within the timeframe of the project became a real challenge, particularly for poplar SRC. It should be noted that dedicated energy crops take time to establish, so a stable market environment is required for the industry to succeed.

14.1.2 Predicted versus actual soil type

As well as the issues with overall feedstock availability, it became apparent that the targeted mix of soil types would not be achievable for any of the chosen project feedstocks across all climate zones, as discussed in Section 3. The soil types that were predicted by the GIS system were, in many cases, different to those determined by analysis of soil samples. This raises concerns about the accuracy of GIS data when applied to localised areas of land. Since the predicted soil types in England were based on the national soil map of England and Wales at 1:250,000 resolution while for the existing forestry sites, more detailed 1:10,000 Forestry Commission soils maps were used, the base data are likely to be the best available therefore the discrepancy is more likely to be related to scaling down to estimates for individual fields.

14.1.3 Climate zone availability

While the project design included looking at the impact of climate zone, it should be noted that not all feedstocks will be commercially grown across all climate zones. The two primary UK climate zones were selected for each feedstock, although the combination of this with soil type led to an uneven geographic distribution of sites for some feedstocks (see Figure 4-1). While the sampling design is appropriate for the project's objective there are some points to consider. Firstly, any comparison of the impact of climate zone across feedstocks should be done with caution. For example, spruce SRF was sampled across a much wider geographical area than poplar SRF so it is reasonable to expect that climate would have a greater effect in spruce than poplar SRF. Secondly, climate zone was rarely influential in this project but this should not be used as a generalisation outside the range encompassed

in the project. Considering the findings themselves, the limited impact of climate zone may be due to a lack of actual difference in growing conditions during the crop's development, to the expectation that differences would be indirect through the impact of growing conditions on growth rate and therefore limited in magnitude, and the comparatively limited sample size. Lastly, the distinction between climate and weather should be made, with weather likely to have a more significant impact on annual crops and climate on those feedstocks with longer growth cycles.

14.1.4 Data quality assurance and interpretation

As discussed in Section 2.6.2, the collected data underwent several levels of review. A very small proportion of the data points were excluded from the statistical analysis, which indicates high standards of sampling and analytical procedures. The results of the statistical analysis were also reviewed for operational relevance, with many of the observed effect and/or relationships excluded from further consideration. However, it should be noted that the review of operational relevance was based mainly on the use of biomass in combustion plant; some of the less critical chemical parameters may have greater significance for other conversion technologies.

14.1.5 Field sampling approach

It should be noted that a manual sampling approach was used throughout this project. This was necessary to avoid contamination with soil, litter or other detritus which had the potential to compromise the results. However, this will not reflect commercial operational practice, where contamination might occur. As a result, levels of e.g. ash may be lower in the project samples than could be expected from bulk harvesting.

The decision was made to sample the spruce SRF trunk, tops and bark separately; however the proportions of each were not measured so it was not possible to calculate the average composition for the whole tree. While values for wood and bark proportions for spruce are available from the literature, these are generally for much older trees. The sampling approach was informed by our understanding of the most likely practice – spruce bark is sold separately in some circumstances whereas poplar is not debarked.

Commercial practice is to plant poplar and willow SRC as a mixture of different varieties to counteract pest attack. In order to minimise variability due to varietal differences within poplar SRF, four trees of each of three varieties (Gaver, Ghoy and Gibecq) were sampled at each site in both Study 1 and 3. For willow SRC it was more difficult to identify varieties in their leaf-off condition, so identical varieties could not be sampled across all sites. The impact of different varieties are investigated further in Phase 2 of the project.

14.2 Results

Comparison of the different feedstocks in Studies 1 and 3 clearly shows that they varied in key fuel quality parameters that can have a significant impact on conversion technologies; a similar impact due to plant part was also noted. For example, the dry ash-free gross calorific value (GCV) was lowest for *Miscanthus* and in the woody biomass, increased in the order trunk wood< tops≈bark and was highest in the leaves. However, due to moisture and ash differences the net calorific value (NCV) on an as received basis was highest for *Miscanthus*, with the different plant parts broadly equivalent for the woody biomass.

Ash on a dry basis was low in the spruce/poplar SRF trunks, willow SRC and *Miscanthus* but was higher in the spruce/poplar SRF tops and spruce SRF bark and especially high in the

poplar SRF and willow SRC leaves. The latter result was expected, given the high metabolic activity and associated mineral containing complexes in leaves. Sulphur and nitrogen concentrations were generally very low in the SRF trunks, increasing in the order; willow SRC stems≈*Miscanthus*< tops≈bark and finally leaves. This order was similar for chlorine, except that the concentrations in *Miscanthus* were elevated and similar to those of the leaves from Study 3.

Certain trace elements showed some intriguing differences between feedstocks and plant parts, though for most concentrations were low - often at or below the limit of detection - and broadly similar across all feedstocks and plant parts. The ash composition was most noticeably different in *Miscanthus* where silica dominated, whereas the ash of the other feedstocks was dominated by calcium compounds.

Comparison of equivalent plant parts for the poplar and spruce SRF demonstrates that the spruce samples generally contain lower concentrations of most chemical components; the spruce bark was also much lower in ash content, and hence a much better fuel than was expected. This may be due to a combination of the care taken during harvesting to avoid contamination and the relatively young age of the trees, which would therefore be expected to have accumulated fewer atmospheric pollutants than more mature forest usually harvested. The levels of ash, chlorine content and calculated alkali index for the *Miscanthus* samples were also interesting to compare against the other data in light of the general industry perception of this feedstock as being 'problematic' (Table 4-2), showing that they were actually similar to the SRF spruce and poplar tops for these parameters.

In light of the potential advantages of these biomass feedstocks for conversion (especially relative to coal), there is scope to use them for co-firing in coal-fired plant. In addition there is scope to make use of the individual strengths and weaknesses of these biomass feedstocks by mixing them to achieve a bio-blend that matches the requirements of the biomass conversion plant. The most realistic approach would be to blend these feedstocks at the point of use or at an intermediate re-processing plant (for example by producing mixed pellets). Growing and harvesting multiple feedstocks in combination to produce a mixed fuel at source, for example mixed poplar and spruce SRF plantations, is unlikely to be satisfactory because of their different site requirements. Although the use of leaves and needles should be acceptable in conversion plants set up to take account of their nitrogen and chlorine levels, the use of these components should also be reviewed from the perspective of site sustainability. This is of particular relevance on nutrient poor sites, however experimental and modelling studies of whole tree harvesting of conifers suggests that atmospheric inputs of nitrogen tend to compensate for those lost in harvesting, even where the fine branches including needles were removed.

Structured analyses were undertaken using four factors (climate zone, generic soil type, harvest time and storage impacts) and combinations thereof. In most cases, overall soil type was not a key determinant of feedstock characteristics, although it should be noted that the range of soil types seen in the project was limited. In contrast harvesting time (which was tested for SRF crops only) and storage had a marked effect on the feedstocks.

The soil analysis data revealed that the sites were very 'clean', with below average or very low levels of soil metals and metalloids, which probably explains the absence of any impact of soil type and the very small number of strong correlations found between feedstock ash characteristics and soil properties. Willow SRC leaves tended to have the strongest correlation between feedstock ash characteristics and the soil composition; this could be due

to the fact that several of their soils had considerably higher heavy metal levels than the other sites, being at or just above the UK average.

Climate zone had little influence on overall feedstock characteristics, except on moisture and its related attributes within a feedstock; other characteristics were not significantly different across the different climate zones.

All feedstock types, with the exception of the willow SRC, reduced in moisture content from point of harvesting to sampling at the end of the storage period. The impact of storage was more marked for SRF, which was stored for three months, than for *Miscanthus* and willow SRC, which were stored for one month.

Where harvesting time was investigated (poplar and spruce SRF) there was often an important impact on feedstock properties, especially on the tops. It should be noted that for the poplar SRF, due to the timing of the project, by the time of the second harvest the poplar was in full leaf and so these samples may have contained leaf material (particular in the fresh material).

Only limited statistical analysis of crop management practices was possible, but this identified possible relationships between year of planting and both cadmium in *Miscanthus* and sodium in willow SRC. The age of sampled material appeared to influence several characteristics in both willow SRC and spruce SRF bark, whilst planting density had impacts on levels of barium in spruce SRF wood as well as the volatile matter, nitrogen, copper and cadmium in spruce SRF tops.

For the in-field variation studies (Study 2), the project investigated feedstock variability within and between sites for *Miscanthus* and willow SRC. For some feedstock characteristics, the variation between the sites was greater than that seen within samples taken from across the same field, whilst for others the variation within-field was much greater than that between different sites. Similar behaviour between the two feedstocks was seen for a number of individual fuel quality parameters. This behaviour is likely to result from a combination of fertilisation requirements vs inherent soil content and the mobility of each element within the soil. For Study 4, a commercial supplier provided raw and pelletised *Miscanthus* samples for comparison. However, it was found that these varied considerably in a number of key parameters; in particular the first two batches of pellets received were contaminated with caustic soda, which is used as an additive to improve pelletisation performance. There was also a tendency for higher levels of some metals in the pellets compared to the raw material, possibly indicating contamination due to the pelletisation process.

A comparison of the data collected within this project has been made with the publically available Phyllis2 database, maintained by ECN in the Netherlands. Large datasets of biomass quality are rare, and while the Phyllis2 database is one of the largest, even here the number of samples of some feedstocks are very low, particularly for the more specialised analysis. Generally good agreement between the datasets was seen for *Miscanthus* and only minor differences noted for willow SRC, with the exception of manganese which was much higher in the project samples. Comparison of the data for poplar and spruce was less reliable as the Phyllis2 does not generally distinguish between different plant fractions or harvest cycle periods, making it unclear whether equivalent samples were being compared. A direct comparison of spruce bark was possible however and indicated that potassium, sodium and phosphorus were higher in the project feedstock, whereas calcium and cadmium were lower than Phyllis2.

Data provided on internationally traded wood pellets by Uniper showed them to be an extremely consistent and homogeneous fuel, with the analysis data tightly clustered compared to the raw woody feedstocks analysed in this project.

A number of quality standards exist for wood pellet depending on the market application and these have recently been defined in ISO17225-2:2014. Depending on which pellet class limits are applied, some of the woody feedstocks from Study 1 would not meet the dry nitrogen and chlorine content, whilst for dry ash, the spruce SRF trunk was the only plant part to consistently meet the strictest limit. In terms of trace elements, the limit for cadmium was the most challenging and was exceeded by a proportion of the poplar SRF dataset (both trunk and tops) and some willow SRC samples, although it is comfortably achieved for all the spruce SRF plant parts. In addition, a few poplar SRF tops and willow SRC samples exceeded some of the limits for copper and zinc. None of the other trace element limits proved to be an issue.

Production costs for different feedstocks were in most cases provided by the feedstock management companies/growers. In general terms, the largest differences between the feedstock types was in the initial establishment and management costs, with spruce SRF and poplar SRF incurring higher costs in the early years. Willow SRC costs were typically higher than *Miscanthus*, largely due to the additional cut back operations at the end of year one, but the difference in costs across all feedstocks was marginal, with an average cost of establishment being less than £1,500/ha for all feedstocks. Harvesting costs were the largest management cost and were noticeably different between feedstocks, with the poplar and spruce SRF incurring the highest costs on a per year per oven dried tonne basis.

14.3 Implications for conversion plant

As shown in Table 3-2, the different feedstock characteristics analysed for in this project can have multiple impacts on conversion plant. For energy production, calorific value of the feedstock (as received at the plant gate) is of primary importance, and the project has demonstrated that this can vary significantly depending on the feedstock type, and in particular the moisture content. It should be noted however that moisture is one of the easiest parameters to change, as shown by the changes on storage, although forced drying is also commonly used, albeit at a cost. Drying may also improve other characteristics such as handleability and resistance to biological degradation.

Levels of sulphur and nitrogen were low compared to coal, although nitrogen in particular was elevated for some plant parts, i.e. the leaves. These elements have a direct impact on gaseous emissions of the respective oxides, which are both considered primary pollutants and hence regulated for many applications. Chlorine contents were heavily dependent on the feedstock, with *Miscanthus* containing some of the highest levels, together with the poplar and willow leaves analysed in Study 3. As well as contributing to acid gas emissions, chlorine is considered to be one of the highest risk elements for boiler corrosion in biomass combustion systems, although these impacts can sometimes be mitigated by the presence of sulphur. Acid gases will also lead to degradation of the amine used in post-combustion carbon capture and storage (CCS) systems and hence high levels of control will be necessary in bioCCS applications. Fuel quality specifications for conversion plant will always include limits on sulphur, nitrogen and chlorine.

Compared to most coals, the ash levels seen in the project feedstocks were low, with the SRF trunks showing the lowest levels. While coal ash is primarily alumino-silicate based, the biomass ash compositions were very different. For most of the feedstocks, the ash was

primarily composed of calcium and potassium compounds; the exception to this was *Miscanthus*, which also contained significant levels of silica. Potassium (and sodium) are linked to a number of detrimental effects within boilers, including slagging, fouling, agglomeration of fluidised beds, corrosion, deactivation of deNO_x catalysts and formation of fine particulate matter. As a result, equipment suppliers will often impose limits on inputs of these elements to the conversion system. Calcium can have positive and negative impacts, the former including capture of acidic gases into the ash (allowing easier removal). The impact on e.g. slagging can vary depending on the presence of other species.

The importance of the trace metals contained in fuel for conversion plant is primarily due to environmental concerns (i.e. air and water emissions), but the feedstocks used in this project were generally so low in these elements for this not to be an issue. Lead and zinc have been identified as presenting a corrosion risk in boilers (particularly in combination with chlorine) and lead in ash may also raise occupational health concerns, but only at higher levels than seen in this project (for example in waste wood combustion).

For the *Miscanthus* pellets, the elevated sodium levels in some of the pellet samples (caused by addition of caustic soda to improve pellet throughput) would have severe consequences for conversion plans in terms of corrosion and fouling. This illustrates that common commercial practice can have significant impact on fuel quality and that good communication between supplier and end-user is necessary to maintain fuel quality.

15 Conclusions

An extensive, robust dataset has been constructed to inform the ETI on the variability in feedstock properties of UK produced energy biomass types, the causes of these variations and the relationship between the feedstock properties and the provenance data collected. The hypotheses can be answered as follows:

1. *The feedstocks examined range from Miscanthus, through woody deciduous plants grown for only a few years and regenerated by coppicing (willow and poplar), to small deciduous and evergreen trees (poplar and Sitka spruce respectively), therefore we hypothesise that the feedstocks will differ in their fuel properties and/or composition.* Significant variation was seen between the different feedstocks in terms of their fuel properties and composition in terms of both the means and the range of the data. For example, the *Miscanthus* showed higher levels of chlorine than the spruce SRF. The importance of this variability will differ depending on the chemical parameter and the conversion system being considered.

2. *With the exception of Miscanthus, the feedstocks are differentiated into plant parts that have different functions, e.g. mechanical support versus photosynthesis; therefore we hypothesise that these plant parts will differ in their fuel properties and/or composition.* This hypothesis was investigated for willow SRC, poplar SRF and spruce SRF and the results indicated that plant part did have a significant impact. Generally, levels of chemical elements were highest in the leaves (where analysed), followed by the tops and bark. The lowest concentrations were found in the trunk wood. Biological material when in active growth has cells containing high levels of genetic material and all the compounds necessary for cell division, maintenance and growth as well as photosynthesis. As active growth, then photosynthesis, then finally maintenance ceases, cell contents are moved elsewhere and the cell wall, which is essentially inert, is left to fulfil a support function. This is also relevant to the impact of time of harvesting addressed in point 5 below.

3. *Feedstock properties will differ depending on the climate the crop is exposed to.* Within the range of average climate zones covered in the project, climate zone had little influence on fuel composition.

4. *Feedstock properties will differ depending on the soil composition and characteristics of the site.* Within the range of soil types determined in the project, soil type had very little influence on fuel properties and/or composition. Similarly, the analysed soil parameters showed few correlations with the corresponding feedstock composition.

5. *Feedstock properties will differ according to the time of year that the biomass is harvested.* This hypothesis was only investigated for poplar and spruce SRF. Feedstock properties of both did differ when harvested in the spring compared to summer harvests, with an impact on the poplar SRF particularly apparent. These differences were more pronounced for the tops than the lower part of the stem; for the poplar SRF this may be due to the inclusion of leaves in the second tops harvest that are essentially absent from the first harvest.

6. *Feedstock properties will differ with storage.* Storage had a strong influence on most feedstocks, particularly for moisture content and related properties for *Miscanthus*, poplar SRF and spruce SRF. In this instance storage of willow SRC had no operationally

important impacts but this finding should not be assumed to be a generalisation as the storage time was only one month.

7. *Within a given field, feedstock properties will be relatively uniform.* This hypothesis was investigated for *Miscanthus* and willow SRC. For some feedstock characteristics, the variation within fields was much greater than that between different sites. Similar behaviour between the two feedstocks was seen for a number of individual fuel quality parameters.

8. *The process of pelletisation will influence the fuel properties and/or composition*. There was a marked change in physical properties of *Miscanthus* following pelletisation. The results indicated that there was a relatively high risk of product contamination, either from deliberate use of additives, from other materials or wear products from the grinding process or the pellet mill itself. However due to the limited number of samples available from the pelletisation process no clear conclusions could be made on changes to the chemical compositional aspects which were not directly related to the additives used by the pellet producer.

A qualitative ranking of factors affecting the important characteristics extracted from the analysis of the individual feedstocks indicates that feedstock characteristics are not affected in a consistent way by the site properties and crop management. Nevertheless, the following general suggestions can be made. The implications for growers of *Miscanthus,* poplar SRF and spruce SRF are that the most important factor affecting moisture and NCV, i.e. storage, can be manipulated. In the case of *Miscanthus,* some of the chemical properties might be modified by the selection of fields, whereas most of the key macronutrients are primarily dependent on the climate zone. With a better understanding of the impact of environment on the growth of *Miscanthus*, sections of the farm could be chosen that would optimise the feedstock properties (and yield). Willow SRC growers have a reasonable degree of control over some of the important feedstock characteristics by their choice of harvesting time – as a means of controlling leaf content– the age of the root stock and the length of the cutting cycle. For poplar SRF and spruce SRF, besides moisture content and NCV which are mentioned above, many of the other properties can be adjusted by the choice of the plant part to market and harvest time. Feedstock properties were relatively insensitive to the way spruce SRF was grown. For all feedstocks, the implications for buyers are that consideration must be given to the feedstock characteristics of prime importance in a particular application.

16 Recommendations

For future studies of this type it is recommended that soil data are collected prior to harvest to better inform site selection, especially if soil type is a factor for inclusion in a balanced experimental design. Sufficient information could be provided by a relatively inexpensive and quick determination of the percentage of sand, silt, clay and organic matter in a representative soil sample. In addition, experience from other relevant projects such as ELUM should be considered with the aim of providing a default initial approach to soil categorisation for use in site selection in future assessments of feedstock characteristics. It is acknowledged however that visiting every potential site considered for inclusion in a project is not an insignificant undertaking and would take considerable time, effort, and cost to achieve before the main project could commence.

The soils featuring in this contract were low in heavy metals when compared to the documented UK average levels, and do not necessarily reflect the feedstock characteristics of crops grown on amended soils. The future use of soil amendments using bio-based fertiliser products (instead of oil based fertiliser products), e.g. composts, sludges and grey water, on sites used for bio-energy production should be estimated and further work comparing potential side effects should be considered and reviewed in more detail. If soil amendments are likely to be carried out on a significant scale in the future, their impact on key feedstock characteristics should be measured. An efficient short-term approach would be to search for sites that have been remediated with known (i.e. quantity and quality) amendments within the recent past, for example within the last five years, and sample any grasses, shrubs, or trees already growing on the site. These could be considered as analogues for *Miscanthus*, willow SRC and deciduous or coniferous SRF to get an early indication of the impact of high heavy metal loads on feedstock characteristics. A longer term approach would be to set up experiments using controlled amendments and specific crops.

While the usual assumption is that bark has highest ash content of all spruce plant parts, this was not observed in this project. The most probable explanations are that the project samples were collected in a way that deliberately avoided contamination and that SRF bark is younger than the bark separated from trees in more traditional forestry which are harvested after much longer rotations. Ash in bark samples from large-scale commercial harvesting should be compared with the data from this project to check if soil and other particulate matter with high levels of ash are routinely trapped in the bark. This could be investigated further by collecting bark samples carefully (using the protocols established in the present project) from stands of different ages but from the same species and general location and also from bark extracted from comparable mature trees after harvesting at various points through typical supply chains to the point of use. If this entrapment is of commercial significance, systems to minimise contamination should be investigated.

The elevated levels of critical fuel components in some of the feedstocks may limit their use as single feedstocks in some conversion technologies. However, opportunities for blending or other pre-treatment to improve the quality and consistency may exist and appropriate tools and methods should be developed to support this option.

It became apparent that the use of additives during the pelletisation process is commonplace for some species and it is recommended that further investigation is done into this area, with further comparisons between the raw and pelletised feedstocks. This should include a review

of the additives used in both industrial and non-industrial pellets (where less quality data is available) and their potential impacts on conversion plant.

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19 Glossary

Agglomeration The formation of lumps of partially sintered ash within a fluidized bed as a result of ash softening at high temperature.

Alkali index A compound parameter expressing the ratio of the sum of the alkaline oxides (usually just of K_2O and Na_2O) to the gross calorific value. The alkali index gives an indication of the tendency of the ash to slagging and fouling. AI >0.17 and fouling is probable; AI>0.34 and fouling is certain.

$$AI = \frac{kg(Na_2O + K_2O)}{GJ\ (GCV)}\ (\text{dry fuel basis})$$

Arboriculture The science and practice of the cultivation and management of individual trees, as distinct from that of large populations of trees (silviculture).

Ash content The total non-combustible mineral content of a fuel. It is expressed as the total mass of the products of complete combustion at a specified temperature; for biomass this is 550°C. It is sometimes assumed these are all oxides, however for calcium in biomass it is more appropriate to assume it is the carbonate ($CaCO_3$). Ash content will not be the same as actual total mineral content of the fuel as the compounds will include oxygen both already present within the fuel, and from the atmosphere.

Ash Fusion Temperatures (AFT) This test is designed to characterise the melting behaviour of a fuel ash. A small cone of ash is heated at a constant rate, 5°C per minute, from 900°C up to a maximum of 1400° to 1500°C (depending on furnace capability) and the temperatures at which specified physical changes occur are noted. These are as follows:

- Initial Deformation (IDT) – the temperature at which the tip of the cone first shows signs of melting
- Softening (ST) – the temperature at which the cone has collapsed so that the height is the same as the base
- Hemisphere (HT) – the temperature at which the height is equal to half the base
- Flow (FT) – the temperature at which the height is one sixth the base.

As Received (AR) This is the analysis of the raw fuel “as received” by the customer and is the basis for the determination of NCV and, therefore, the price.

Billet Lengths of harvested SRC material of typically 5 – 20 cm when it is harvested using a billet harvester. This harvests whole stems and then cuts them into length. Billets tend to dry better than chips owing to better air flow within the stacks, but are less easy to chip subsequently.

Bioenergy	Any energy derived from some form of biomass or biological material or another.
Biomass	Material that is derived from living, or recently living, biological organisms. In the energy context it is often used to refer to plant material, however by-products and waste from livestock farming, food processing and preparation and domestic organic waste, can all form sources of biomass. In the context of this report however it refers to plant material.
Bulk density	The overall density of a volume of fuel as delivered, including both the solid fuel and the interstitial air spaces.
Cation Exchange Capacity (CEC)	The capacity of soils to hold exchangeable cations (such as K^+, Ca^{2+}), which influences its ability to hold nutrients and to buffer acidification. A higher proportion of clay or organic matter tends to increase CEC.
Clone	The individual varieties of willow and poplar used commercially for SRC or SRF are propagated vegetatively, and are consequently genetically identical. All examples of a variety are therefore a clone of the others.
Dry	This is the analysis quoted on the basis of the fuel with the moisture content discounted.
Dry Ash Free (DAF)	The dry ash free analysis is that with both the moisture and ash discounted, i.e. the total inert content. For coal characterisation, the DAF calorific value and volatile matter are vital as they describe the nature of the actual fuel matter. The moisture and ash are simply inert diluents that have to be handled to obtain the heat in the fuel.
Durability	An important parameter within the EN Standards specification for pellets which defines their resistance to crumbling and breaking down to sawdust during handling and transport. Measured as a percentage of the fuel by weight that remains after mechanical agitation and removal of the resultant fines.
Energy crop	Crop planted specifically to produce a regular supply of biomass for energy. Crops are selected on the basis of ability to produce high yield per hectare with no, or minimal, requirement for fertilizer inputs.
ENPlus	A specification for wood pellets that meet the standard for one of the grades of non-industrial pellets A1 to B set out in BS EN 14961-2.
Eutectic	A mixture of chemical species that has the effect of reducing the melting point of the mix below that of the individual constituents, such that it all melts at a single temperature. In fuel ash this can produce a low melting point ash that increases the likelihood of slagging and fouling.
Feedstock	Raw biomass from which biomass fuel can be made.

Fines	The proportion of a biomass fuel that falls below the minimum size threshold. Typically 3.15 mm.
Fouling	Deposition of ash onto components in the cooler, convective regions of a combustion appliance. This is defined as the formation of sintered deposits in the high temperature convective pass of a combustion appliance. Temperature range 1200°C down to about 950°C.
Glyphosate	A broad spectrum herbicide widely used for weed control especially during crop establishment. The basic ingredient of the commercial product Roundup.
Graphic Information System (GIS)	A computer based system presenting maps that can be overlaid with layers presenting different types of geographical information such as meteorological, geological, agricultural or other type. In this project we have used GIS layers to present broad climate zone classifications and soil types to assist us in our initial selection of sample sites to try to obtain an even distribution of climate zone and soil type.
Gross Calorific Value (GCV)	The total energy available from combusting a unit quantity of fuel. It assumes that the products of combustion are brought back to the pre-combustion temperature and water vapour produced as a result of oxidation of hydrogen in the fuel condensed and the latent heat of vaporization (enthalpy of vaporization) of the water recovered. GCV is the same as Higher Heating Value (HHV)
Heavy soil	A soil with a clay content >35%
Hesston bales	Large bales of straw, hay or grassy crop such as *Miscanthus*. Standard bale size for UK *Miscanthus* growers is 120 cm x 125 cm x 250 cm and weigh about 600 kg.
Higher Heating Value (HHV)	See Gross Calorific Value (GCV)
Leaching	The loss of soluble mineral content as a result of washout by water, especially the washout of minerals in soil by rain.
Light soil	Soil with a low clay content of 18% or less
Lower Heating Value (LHV)	See Net Calorific Value (NCV)
Macroelements	The principle (ash forming) elements in the biomass feedstock or soil, excluding the minor (or trace) elements and the structural elements in biomass of carbon, hydrogen oxygen and nitrogen. In biomass feedstock samples the macroelements are: Aluminium (Al), Potassium (K), Sodium (Na), Calcium (Ca), Silicon (Si), Magnesium (Mg), Iron (Fe), Phosphorus (P) and Titanium (Ti). In the soil samples the macroelements are Nitrogen, (N), Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg).

Medium soil	Soils with a clay content between 19% and 35% in the topsoil
Mineral soil	Soil with a relatively low proportion of organic matter. The actual percentage of organic matter depends on the percentage of clay in the soil. From 0%-50% clay the cut-off increases linearly from 6%-10%, but above this it remains at 10% organic matter.
Miscanthus	Fast growing perennial energy crop that is harvested annually and can give high yields with no fertilizer inputs. *Miscanthus* makes use of C_4 carbon fixation, rather than the more common C_3 process used by most plants, which makes it very efficient at photosynthesis. The variety used commercially within the UK is almost exclusively *Miscanthus X giganteus*.
Moisture content	The percentage of the weight of timber or a fuel that is water. This can be expressed as a percentage of the total weight (wet basis) or a percentage of the weight of the dry matter (dry basis). Moisture content is critical as it has a very significant effect on the net calorific value of the fuel as received. It can also have an impact on the storage properties of biomass fuel.
Net Calorific Value (NCV)	The energy available from combusting a unit quantity of fuel. NCV does not assume that the water vapour produced is condensed and the latent heat of vaporization recovered. NCV is the same as Lower Heating Value (LHV). NCV can be quoted for a fuel with non-zero moisture content, and will consist of the energy available from the fuel content, less the energy required to vaporize the moisture in the fuel.
Normalized ash oxides	The mineral content of the fuel can be expressed as the quantity of each element in the dry fuel, or as their individual proportion of the ash after combustion. To do this requires an assumption of the compound form of each element in the ash. This usually assumed to be an oxide, though for some, particularly calcium, the carbonate is more appropriate for biomass. The ash compounds are normalized so the total of those included sums to 100% of the total measured mass. In this study the levels of individual elements in the dry biomass has been measured directly and normalized ash composition calculated from these.
Organic Matter	The soil component derived from the breakdown of plant and animal matter, as distinct from the mineral component. Organic matter consists of a high proportion of organic carbon and contributes to a high CEC.
Organic soil	Soil with a relatively high proportion of organic matter >6-10% depending on the percentage of clay. From 0%-50% clay the definition of an organic soil increases linearly from 6%-10%, but above this it remains at 10% organic matter

Peat	Soil with a very high organic matter content >50%. Below this level, and above the organic soil classification (20-25% organic matter) are other descriptions such as peaty loam and peaty sand up to 35% OM (depending on the proportion of sand), and loamy peat and sandy peat from 35% to 50% OM.
Pesticide	Generic term used to cover all chemical products used to kill pests of any kind. Products can include herbicides to kill unwanted plants, insecticides to kill insects, fungicides to kill fungal diseases
Phyllis	A database of physical and chemical properties of a wide range of forms of biomass and organic waste hosted by the Energy Centre of the Netherlands (ECN). It contains values measured at ECN itself and also published elsewhere.
Provenance	The origin or history of the feedstock. In the context of this project the provenance data associated with each sample includes information about how and where is was grown, including any preparation of the land, applications of fertilizers, sewage sludge or pesticides, the characteristics of the site including the characteristics of the soil and site and the quality of draining, and the weather during sample collection. Although not necessarily analysed directly, a full suite of data was collected and stored to allow future reference if necessary to allow subsequent interpretation of anomalous or unexpected values or results.
Proximate analysis	Analysis of a fuel or biomass sample to determine the main fuel related properties: moisture content, ash content, volatile matter and fixed carbon.
Rhizome	An underground plant part, consisting of modified stem, from which new stems and roots can grow and allowing propagation. A single rhizome of sufficient size can be divided up and each planted separately to allow multiple new plants to be established. *Miscanthus* is typically planted as rhizome pieces.
Short Rotation Coppice (SRC)	Fast growing tree species cut back close to ground level one year after planting to promote multiple stem growth, and then regularly thereafter on a rotation of a few years; typically two to five for fast growing crops like willow or poplar, up to ten to fifteen for more traditional broadleaf coppice. This produces multiple, slender stems on a regular basis from each stool (cut stump) that can be used for fuel, or traditional coppice products.
Short Rotation Forestry (SRF)	Fast growing tree species grown as a single stem as in conventional forestry, but harvested on a much shorter rotation (typically 15 – 20 years) in order to make use of the period of fastest growth and produce a regular crop of relatively small diameter timber for fuel or other purposes.
Slag	Ash that has fully or partially melted and then re-solidified.

Slagging Deposition of ash that has melted or softened, and solidified in the radiant, high temperature region of a combustion appliance. This is defined as the formation of fused deposits in the radiant zone of the furnace, i.e. the burner quarls, furnace walls and radiant platens. Temperature range 1600°C down to about 1200°C.

Slagging index (R_s) A compound index consisting of the ratio of the sum of the basic oxides (CaO, MgO, K_2O, Na_2O and Fe_2O_3) to the sum of the acidic oxides (SiO_2, Al_2O_3, and TiO_2) (all expressed as percentages in the ash) multiplied by the percentage of sulphur in the dry fuel. A value of $R_s<0.6$ suggests a low slagging propensity, while $R_s>2.0$ indicates a high risk of slagging.

Stool The cut stump of coppice from which new stems grow. While the stems may be only three or four years old, the stool can be up to 25 years old or more.

Structured analysis The statistical analysis of structured data (e.g. in a database) to allow relationships and comparisons to be made in a statistically rigorous manner.

Thinning The selective felling of a proportion of trees within a stand, usually at relatively young age, to reduce the density in order to improve the quality and growth of the remaining trees.

Trace elements Elements present in biomass feedstock, fuel or soil in very low concentrations. They can however be very important in terms of emissions (especially if toxic), and influence ash chemistry and behaviour. They can have either a negative or positive effect on corrosion behaviour, slagging and fouling. In the soil they can have an impact on soil fertility.

Ultimate analysis The chemical analysis of a fuel or biomass sample to evaluate the proportion by weight of all the individual elements including minerals, heavy metals and trace elements.

20 Abbreviations

AFT	Ash Fusion Temperature
AI	Alkali Index
ar	as received (fuel)
BS	British Standard
CCS	Carbon capture and storage
CEC	Cation Exchange Capacity
CEN	Comité Européen de Normalisation
cm	centimetre
CV	Calorific Value
CV%	Coefficient of Variation
CW	Cold/wet
CZ	Climate Zone
d	dry (fuel)
daf, DAF	dry ash free (fuel)
dbh	diameter at breast height
CEC	Cation Exchange Capacity
DECC	Department of Energy and Climate Change
DUKES	Digest of UK Energy Statistics
ECN	Energy Research Centre of the Netherlands
EN	European standard, developed by CEN
ETI	Energy Technologies Institute
FR	Forest Research
GCV	Gross Calorific Value
GIS	Geographic Information System
H1	First harvest time
H2	Second harvest time
ha	hectare
HHV	Higher Heating Value (=GCV)
HT	Harvest Time
IDT	Initial ash Deformation Temperature
IFV	In-field Variation
ISO	International Organization for Standardization

IWPB	Initiative of Wood Pellet Buyers
kJ/kg	kilojoules per kilogramme
kg/m^3	kilogrammes per cubic metre
L	Light (soil)
LHV	Lower Heating Value (=NCV)
LOD	Limit of Detection
M	Medium (soil)
mg/kg	milligrammes per kilogramme
Misc.	*Miscanthus*
MJ/kg	megajoules per kilogramme
mm	millimetre
mth	month
n	(statistics) number of values
na	normalized ash
n/a	not available, not applicable
NCA	Not commercially available
NCV	Net Calorific Value
NOBS	Number of observations
NO_x	Oxides of Nitrogen
NREL	National Renewable Energy Laboratory (US)
ODT, odt	Oven Dry Tonne
OM	Organic Matter
OPEX	Operational Expenditure
p	(statistical) probability
ppm	parts per million
RSQ	R squared
SD	Standard Deviation
SOP	Standard Operating Procedure
SO_x	Oxides of sulphur
SRC	Short Rotation Coppice
SRC-W	SRC willow
SRF	Short Rotation Forest
SS	Sitka spruce
ST	Soil Type

STORE	Storage
TGA	Thermogravimetric Analysis
UK	United Kingdom
US	United States (of America)
VM	Volatile Matter
WD	Warm/dry
WM	Warm/moist
wt	weight
yr	year

21 Appendices

1. Deliverable description and acceptance criteria
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