Programme Area: Bioenergy

Project: Characterisation of Feedstocks

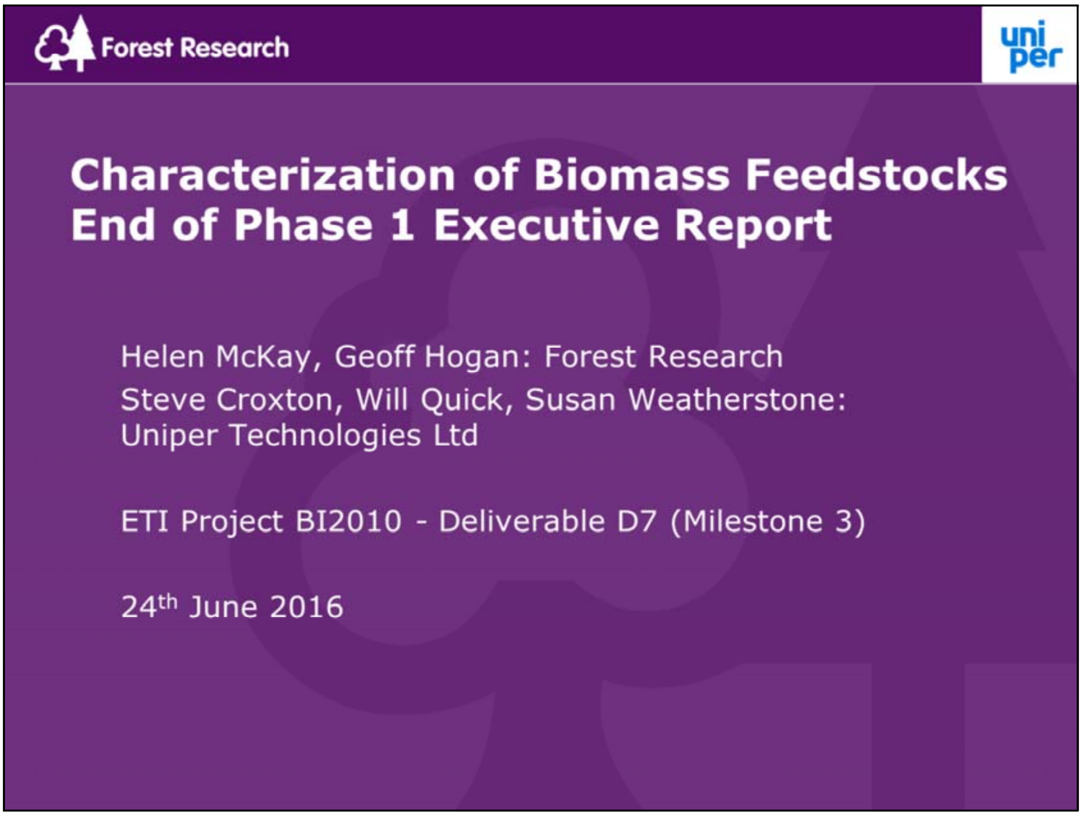
Title: D7 Executive Report

Abstract:

The primary objective of this 2015/16/17 Project was to provide an understanding of UK produced biomass properties, how these vary and what causes this variability.
This 40 page report was the first of seven deliverables to be produced under the first phase (2015/16) of this Project and the first of two under Milestone 1. The purpose of this report was to demonstrate that there was a comprehensive plan in place to deliver the Project and that the Project's requirements would be met. The report provides the following: a schedule of work detailing the list of feedstocks to be sampled; the type, number and source of samples to be collected; a plan for gathering the samples' provenance data; a planned schedule of laboratory preparation and testing to be carried out; a clear plan for delivering the ETI project objectives. Of interest may be the following: rationale for choices made – page 3 (as marked); list of laboratory tests to be performed – page 8 (as marked); list of provenance data collected – page 9 (as marked); sample site locations – page 15 (as marked).

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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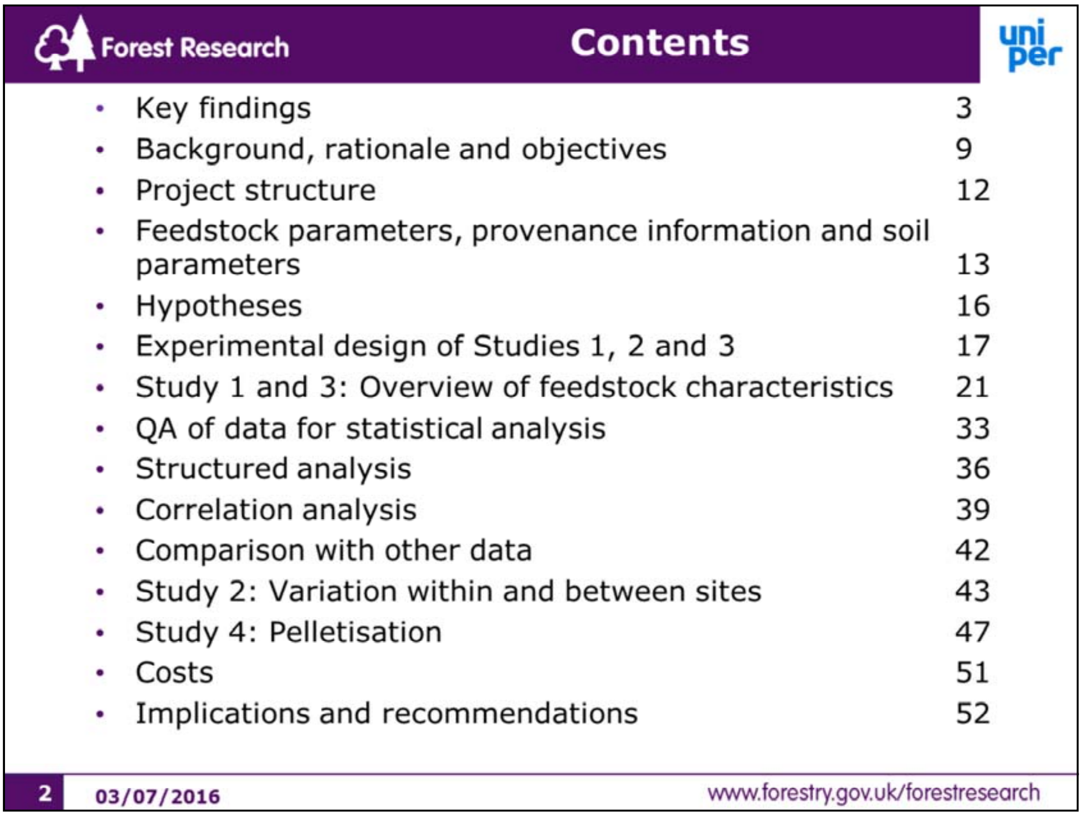
Characterization of Biomass Feedstocks End of Phase 1 Executive Report

Helen McKay, Geoff Hogan: Forest Research
Steve Croxton, Will Quick, Susan Weatherstone:
Uniper Technologies Ltd

ETI Project BI2010 - Deliverable D7 (Milestone 3)

24th June 2016

This presentation gives a summary of the key results from the Characterization of Feedstocks project, undertaken on behalf of the ETI. Greater detail is given in the project report, the accompanying appendices and the database of results.



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Contents

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This presentation will give an overview of the whole project, starting with a summary of the key findings. This is followed by an introduction to the context of the project, including background, rationale and objectives, a description of how we approached the project, including the parameters investigated, the hypotheses tested and the experimental protocol.

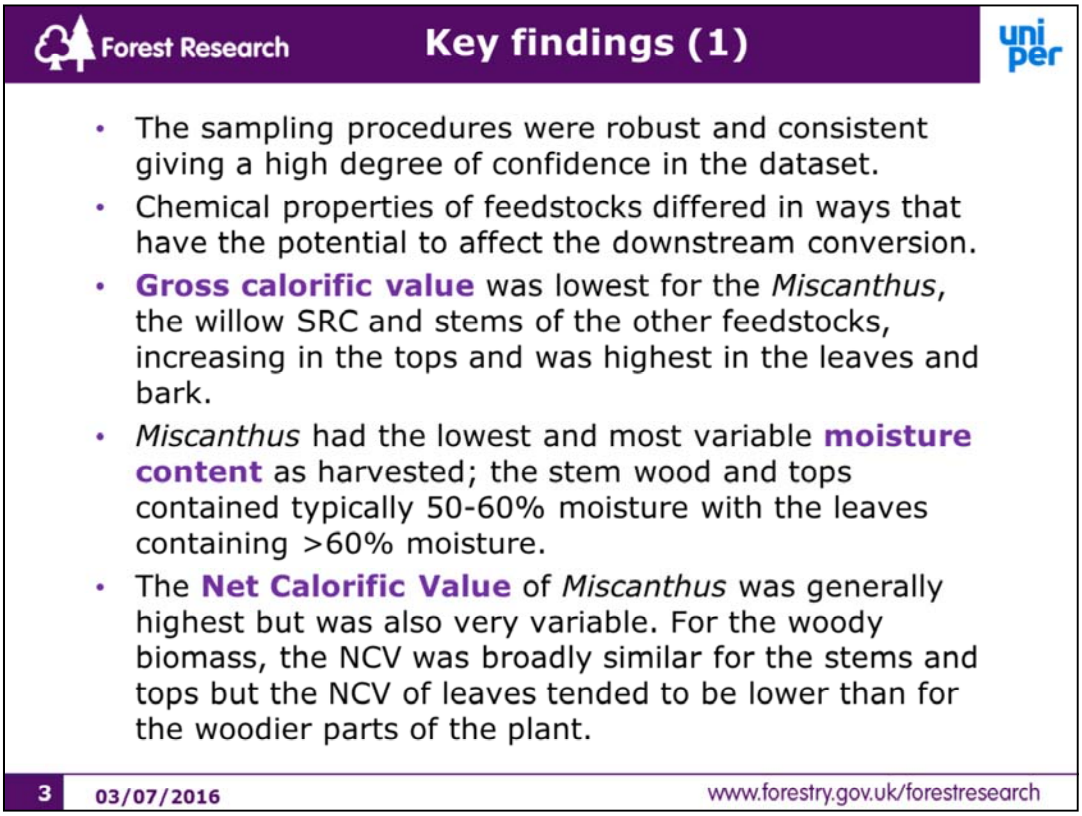
It will then look at the two main areas of study, the results obtained and the statistical analysis employed.

An initial comparison of our results with those in the principal International database of biomass properties will be discussed in order to put our results into context.

The results of the final two areas of study: the comparison of variation within individual fields with that observed between sites, and the effect of pelletisation will be presented.

Some comments will be made on the information obtained on the relative costs of establishment and production of the different feedstocks.

Finally the implications of, and recommendations to be drawn from the study will be discussed.



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Key findings (1)

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- 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.
- **Gross calorific value** was lowest for the *Miscanthus*, the willow SRC and stems 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 stem wood and tops contained typically 50-60% moisture with the leaves containing >60% moisture.
- The **Net Calorific Value** 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.

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The project produced a number of key findings, as set out in this, and the following five slides.

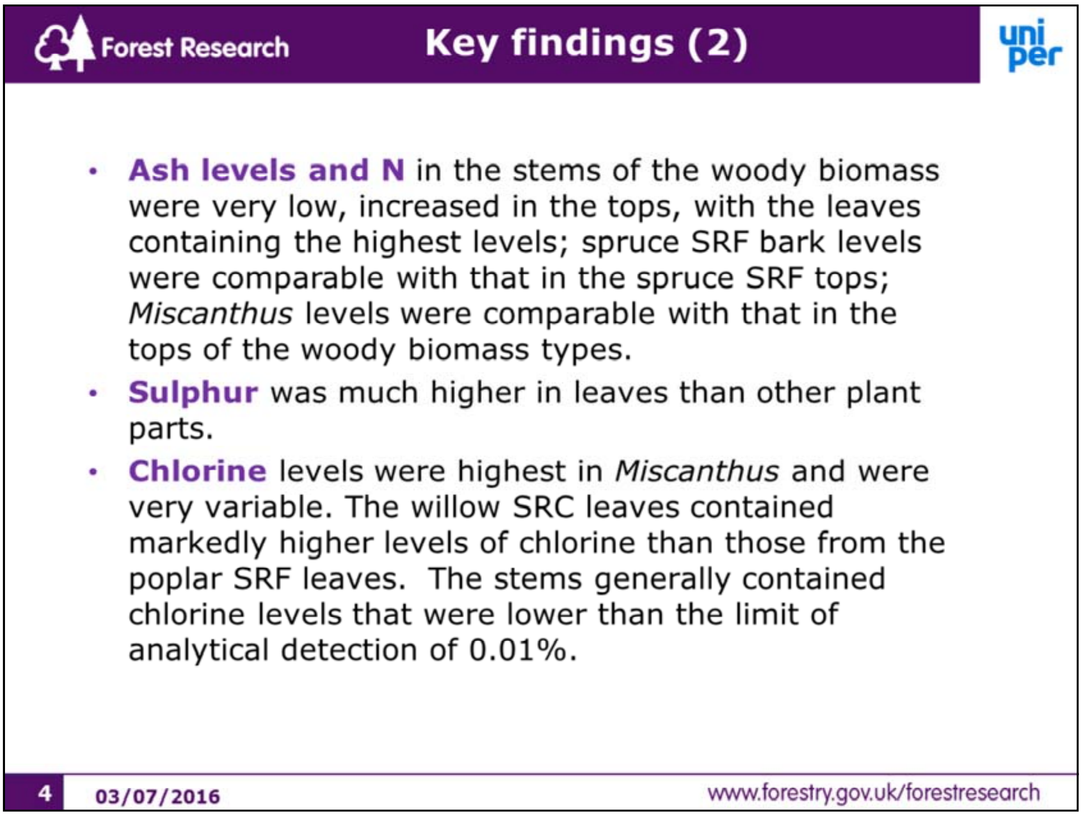
There is a high degree of confidence in the dataset because of the small number of outliers that were excluded from the analysis; the results of some parameters in some feedstocks had very small ranges; and there was relative consistency between harvests and storage time. This is considered to be a result of careful sample collection and handling throughout, robust protocols, well trained staff, and professional staff at all stages.

SRC = short rotation coppice.

DAF GCV = dry ash free gross calorific value and reflects the potential total energy content after drying, excluding the ash content.

Moisture content is the biggest determinant of realizable energy content.

NCV = net calorific value and reflects the actual realizable energy content of the feedstock as harvested, however this can be modified by drying.



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Key findings (2)

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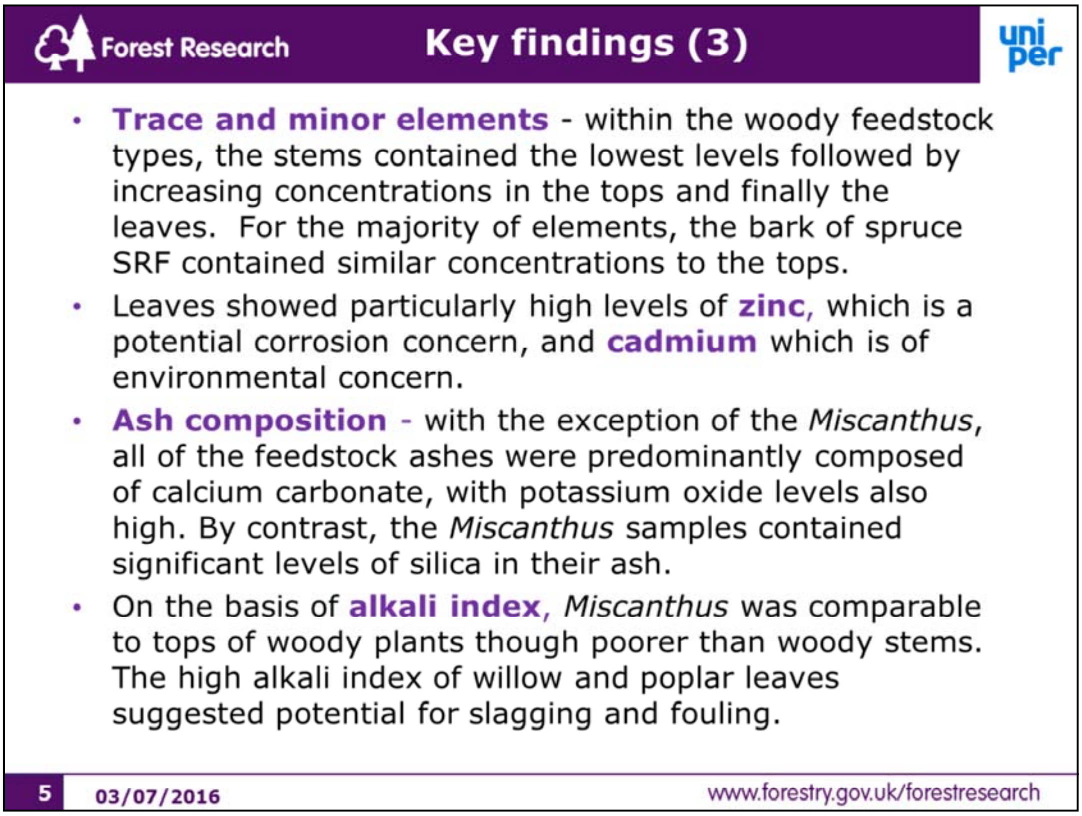
- **Ash levels and N** in the stems of the woody biomass were very low, increased in the tops, with the leaves containing the highest levels; spruce SRF bark levels were comparable with that in the spruce SRF tops; *Miscanthus* levels were comparable with that in the tops of the woody biomass types.
- **Sulphur** was much higher in leaves than other plant parts.
- **Chlorine** levels were highest in *Miscanthus* and were very variable. The willow SRC leaves contained markedly higher levels of chlorine than those from the poplar SRF leaves. The stems generally contained chlorine levels that were lower than the limit of analytical detection of 0.01%.

Ash represents non-combustible, mineral fuel content, but also potential cause of slagging, agglomeration and corrosion. Nitrogen within fuel adds to other sources to increase emissions of NOx, Sulphur both adds to emissions of SOx and can contribute to corrosion within the plant, and chlorine can also lead to corrosion.

It is therefore valuable to compare feedstocks on the basis of these parameters, and also begin to understand the extent of variation in them and the factors that can influence levels.

SRF=short rotation forest.



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Key findings (3)

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- **Trace and minor elements** - within the woody feedstock types, the stems 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.

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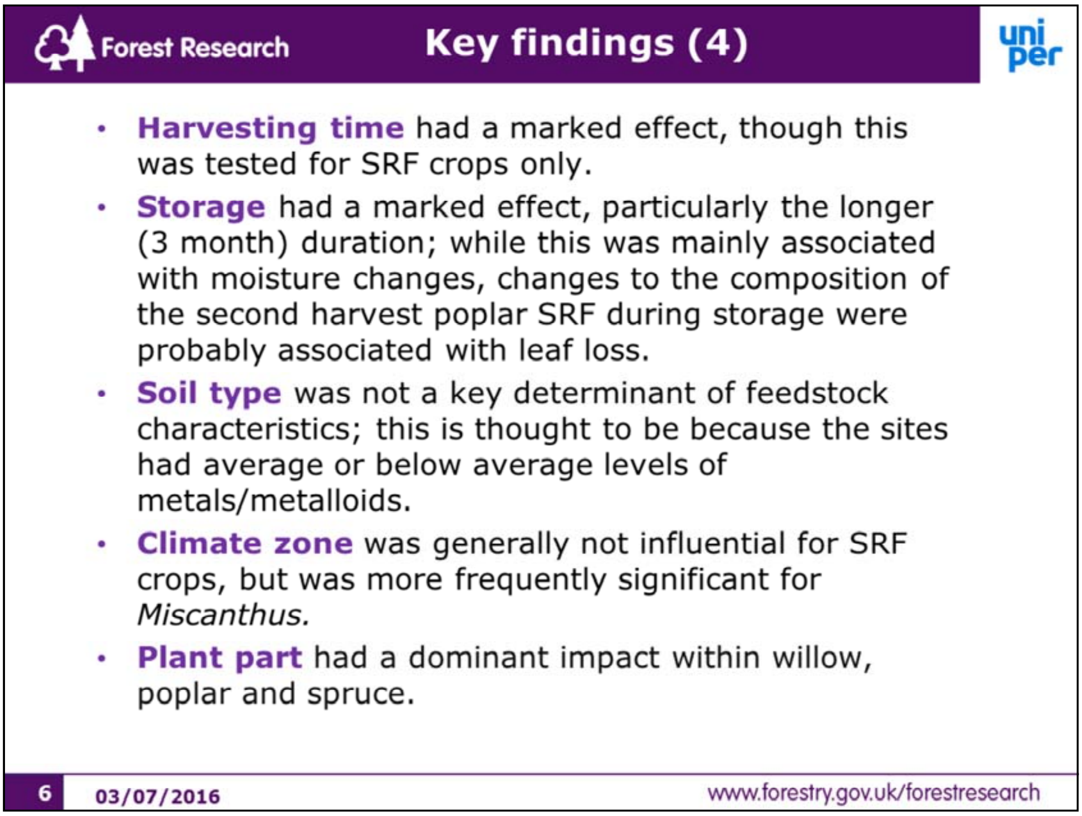
There are also a number of heavy metals and trace elements which may be toxic if emitted to air, or can contribute to slagging, fouling or corrosion.

The specific mix of oxides of (principally) alkali and alkaline earth metals in the ash will influence the temperatures at which it softens and melts, and the ratio of the proportion of alkali oxides to the energy content (expressed as the alkali index) is found to be a good indicator of the tendency to slagging and fouling.

Leaves of willow (SRC) and poplar (SRF) only were tested.



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Key findings (4)

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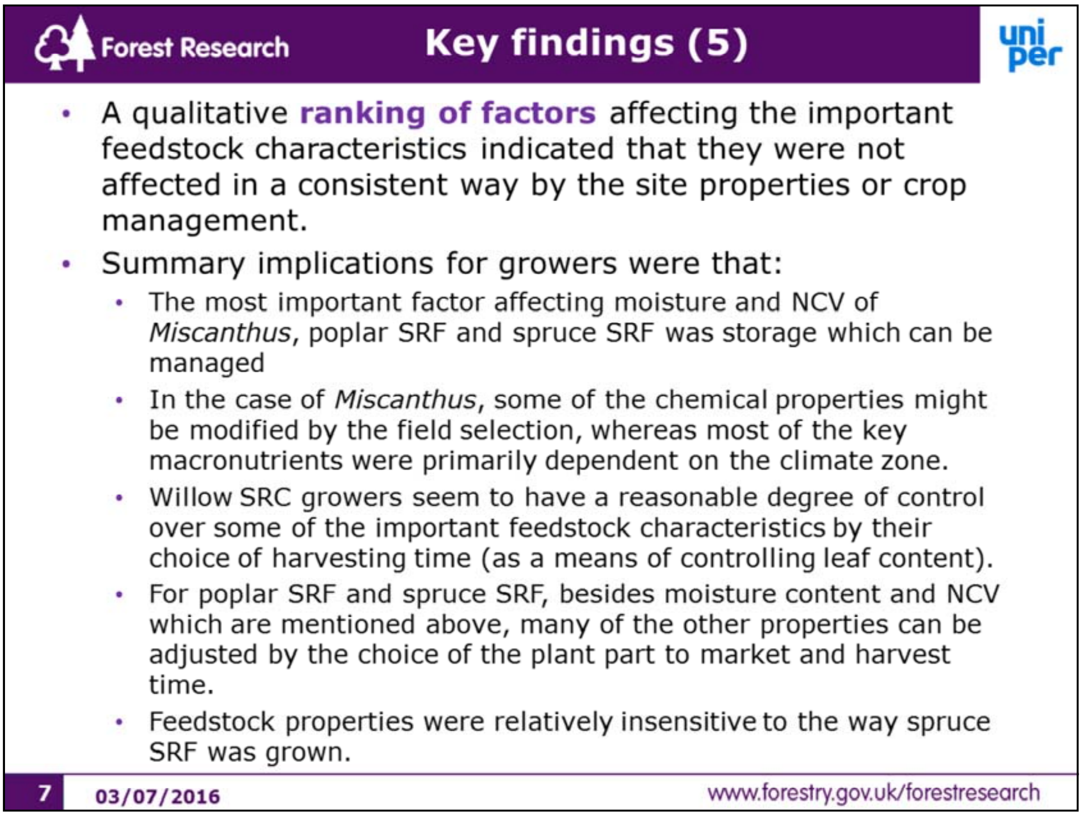
- **Harvesting time** had a marked effect, though this was tested for SRF crops only.
- **Storage** had a marked effect, particularly the longer (3 month) duration; while this was mainly associated with moisture changes, changes to the composition of the second harvest poplar SRF during storage were 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 frequently significant for *Miscanthus.*
- **Plant part** had a dominant impact within willow, poplar and spruce.

A number of variables were investigated in order to attempt to assess their impact on both the physical and chemical properties of the samples, and also the magnitude of variability.

The principal variables investigated are listed on the slide, and the key observations given.



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Key findings (5)

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- A qualitative **ranking of factors** affecting the important feedstock characteristics indicated that they were not affected in a consistent way by the site properties or crop management.
- Summary implications for growers were that:
  - The most important factor affecting moisture and NCV of *Miscanthus*, poplar SRF and spruce SRF was storage which can be managed
  - In the case of *Miscanthus*, some of the chemical properties might be modified by the field selection, whereas most of the key macronutrients were 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.

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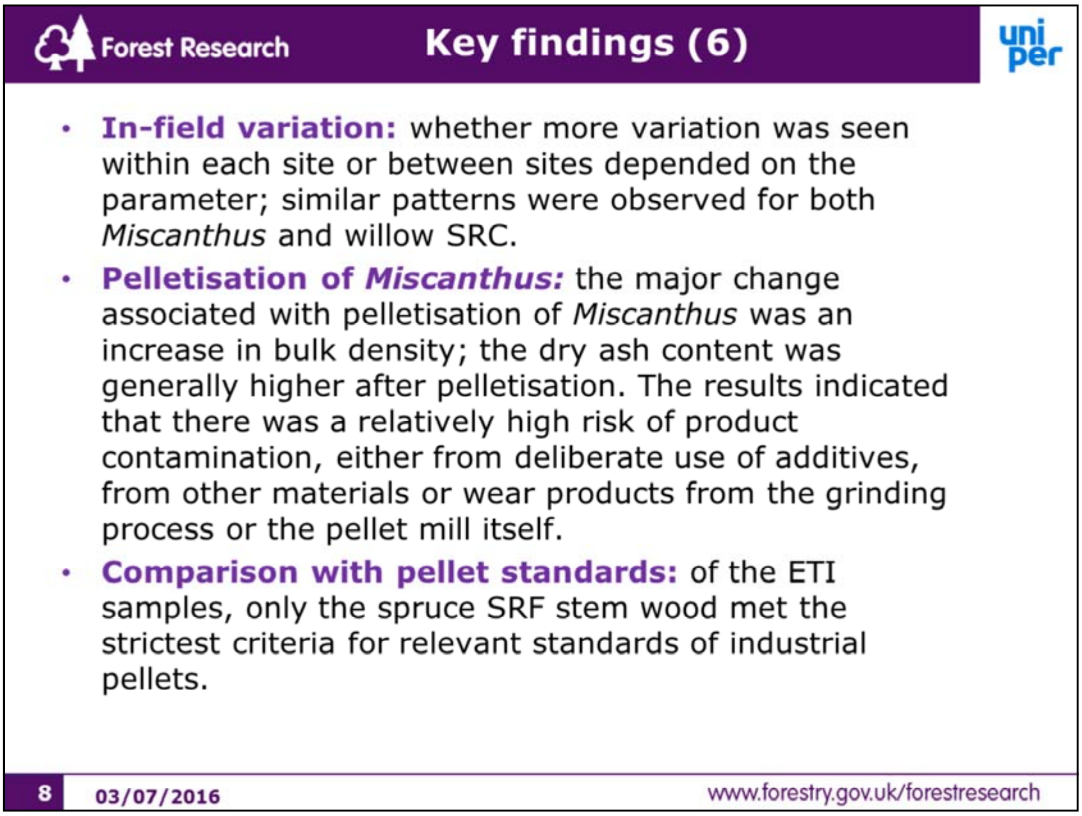
A qualitative ranking was used to evaluate all the site factors and provenance information shown to influence the feedstock properties in a significant way, in terms of their statistical and analytical significance as well as their operational effect. There was no simple common ranking – feedstock characteristics were not affected in a consistent way by site factors or crop management.

The implications for growers are summarised above. In addition to the qualitative ranking also suggested that for all feedstocks, buyers should give consideration to the feedstock characteristics of prime importance in a particular application.



Key findings (6)

- **In-field variation:** whether more variation was seen within each site or between sites depended on the parameter; similar patterns were observed for both *Miscanthus* and willow SRC.
- **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 the grinding process or the pellet mill itself.
- **Comparison with pellet standards:** of the ETI samples, only the spruce SRF stem wood met the strictest criteria for relevant standards of industrial pellets.

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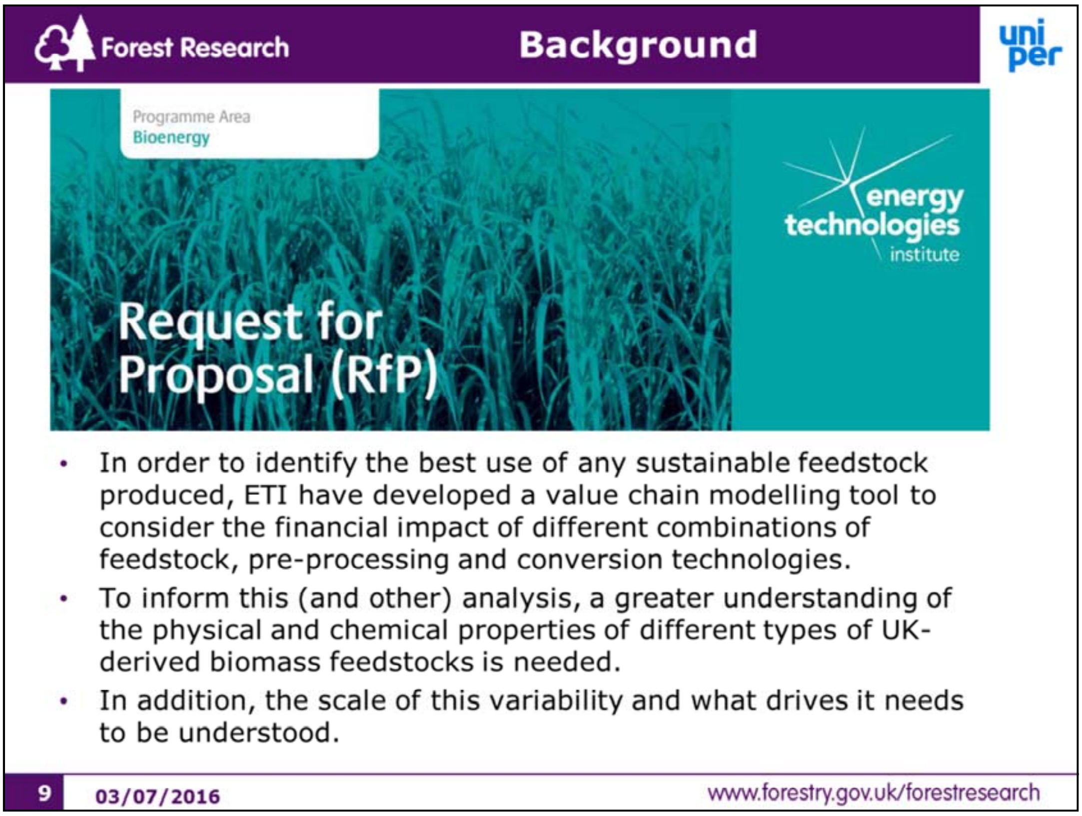
Additional work looked at the impact of pelletisation on properties, including pelletisation of *Miscanthus,* and also the comparison of our measured values for properties of feedstocks with wood pellet standards.

Although the project had access to samples of *Miscanthus* both before and after pelleting, the use of additives during the pelleting process made direct comparison of some properties difficult to evaluate.



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Background

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Programme Area
Bioenergy

Request for Proposal (RfP)

energy technologies institute

- In order to identify the best use of any sustainable feedstock produced, ETI have developed a value chain modelling tool to consider the financial impact of different combinations of feedstock, pre-processing and conversion technologies.
- To inform this (and other) analysis, a greater understanding of the physical and chemical properties of different types of UK-derived biomass feedstocks is needed.
- In addition, the scale of this variability and what drives it needs to be understood.

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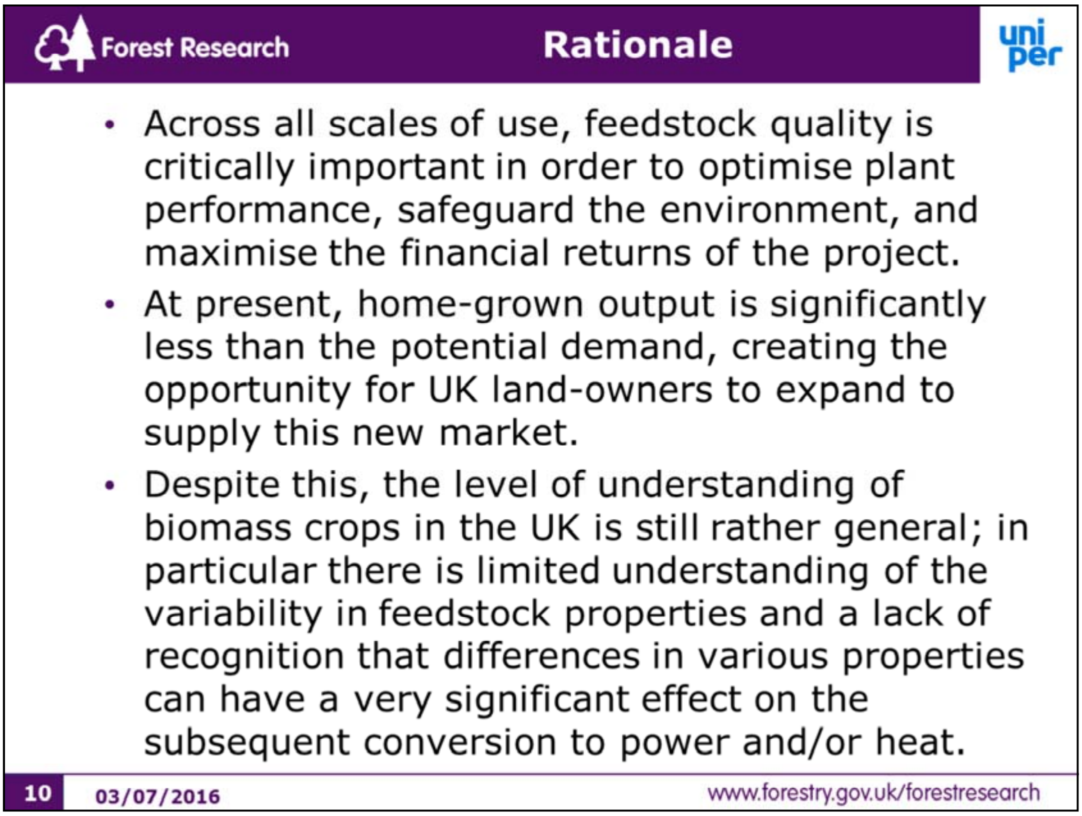
Very clear guidance was provided in the Request for Proposal on:

a. Background

Increasing the sustainable production of biomass captures large amounts of carbon dioxide (CO2) from the atmosphere and the biomass can be used for producing energy and other products. Converting 10% of UK land area (2.4 million hectares) could create 50 or more million tonnes per year of net negative CO2 emission, when combined with Carbon Capture and Storage (CCS) to minimise the release of captured carbon back to the atmosphere. Even without CCS, bioenergy has been shown to deliver carbon savings compared with fossil fuels, and offers significant end-use flexibility.

b. Outcomes sought

In order to identify the best use of any sustainable feedstock produced, ETI have developed a value chain modelling tool to consider the financial impact of different combinations of feedstock, pre-processing and conversion technologies. However, to inform this (and other) analysis, a greater understanding of the variation in physical and chemical properties of different types of UK-derived biomass feedstocks are needed. In addition, the scale of this variability and what drives it needs to be understood.



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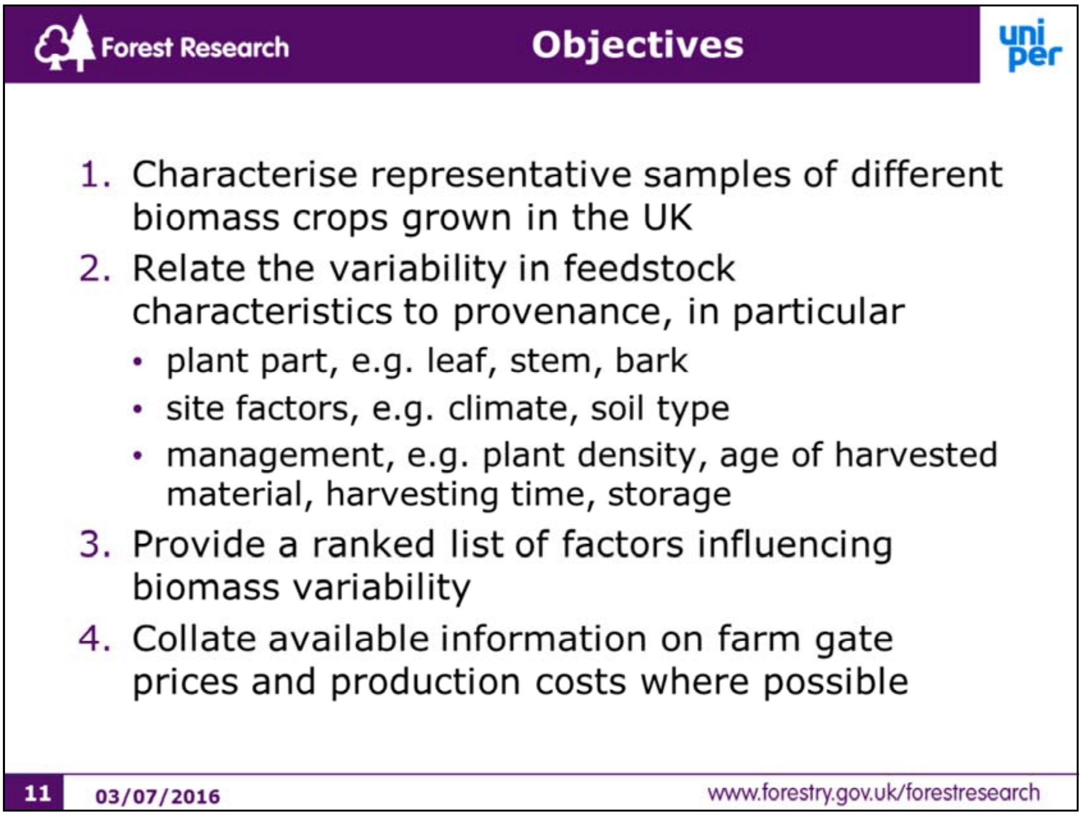
Rationale

- 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.
- At present, home-grown output is significantly less than the potential 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.

This slide sets out the rationale for the project, putting the current poor understanding of the variability in biomass feedstock properties into the context of the requirements for optimal plant performance and financial returns.



Objectives

1. Characterise representative samples of different biomass crops grown in the UK
2. Relate the variability in feedstock characteristics to provenance, in particular
    - plant part, e.g. leaf, stem, bark
    - site factors, e.g. climate, soil type
    - management, e.g. plant density, age of harvested material, harvesting time, storage
3. Provide a ranked list of factors influencing biomass variability
4. Collate available information on farm gate prices and production costs where possible

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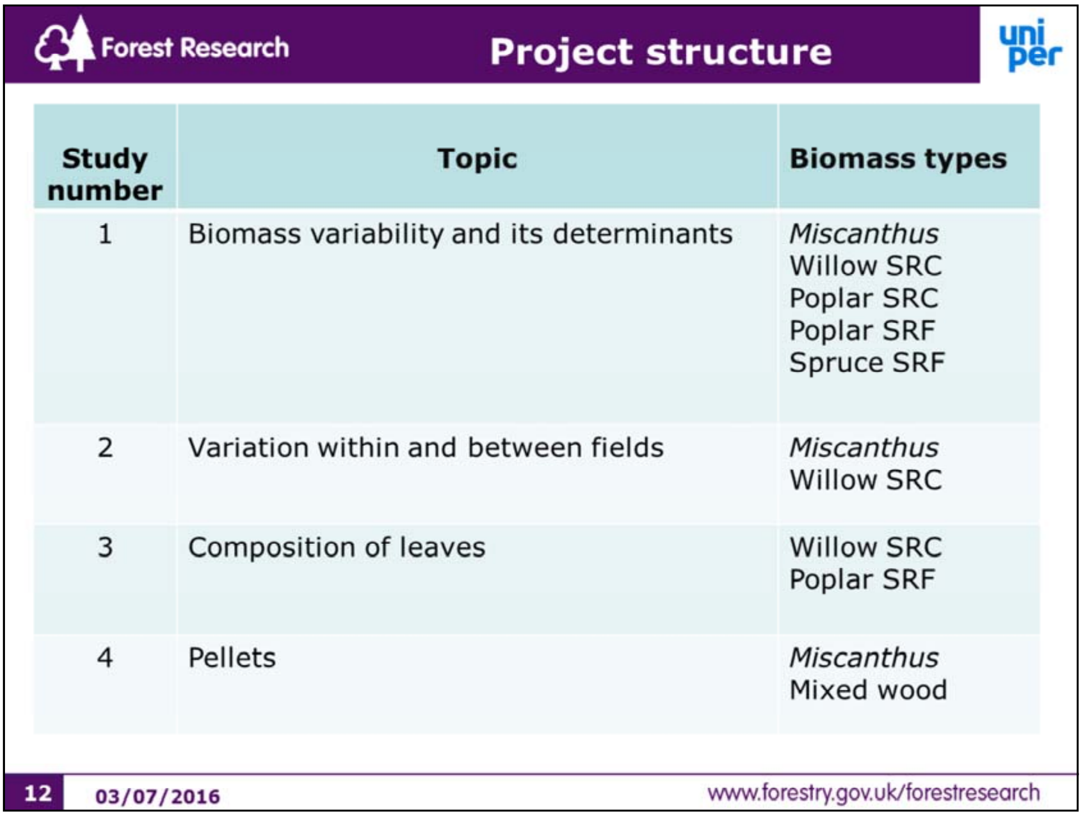
The objectives of the project were to:

- Characterize the properties of a range of biomass feedstock crops from the UK
- Assess the magnitude of variability in the parameters measured and relate it to various factors such as plant part, climate, soil type and management
- Provide a ranked list of factors influencing feedstock variability
- Collect basic information on farm gate prices and establishment and production costs



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Project structure

Study number	Topic	Biomass types
1	Biomass variability and its determinants	*Miscanthus* Willow SRC Poplar SRC Poplar SRF Spruce SRF
2	Variation within and between fields	*Miscanthus* Willow SRC
3	Composition of leaves	Willow SRC Poplar SRF
4	Pellets	*Miscanthus* Mixed wood

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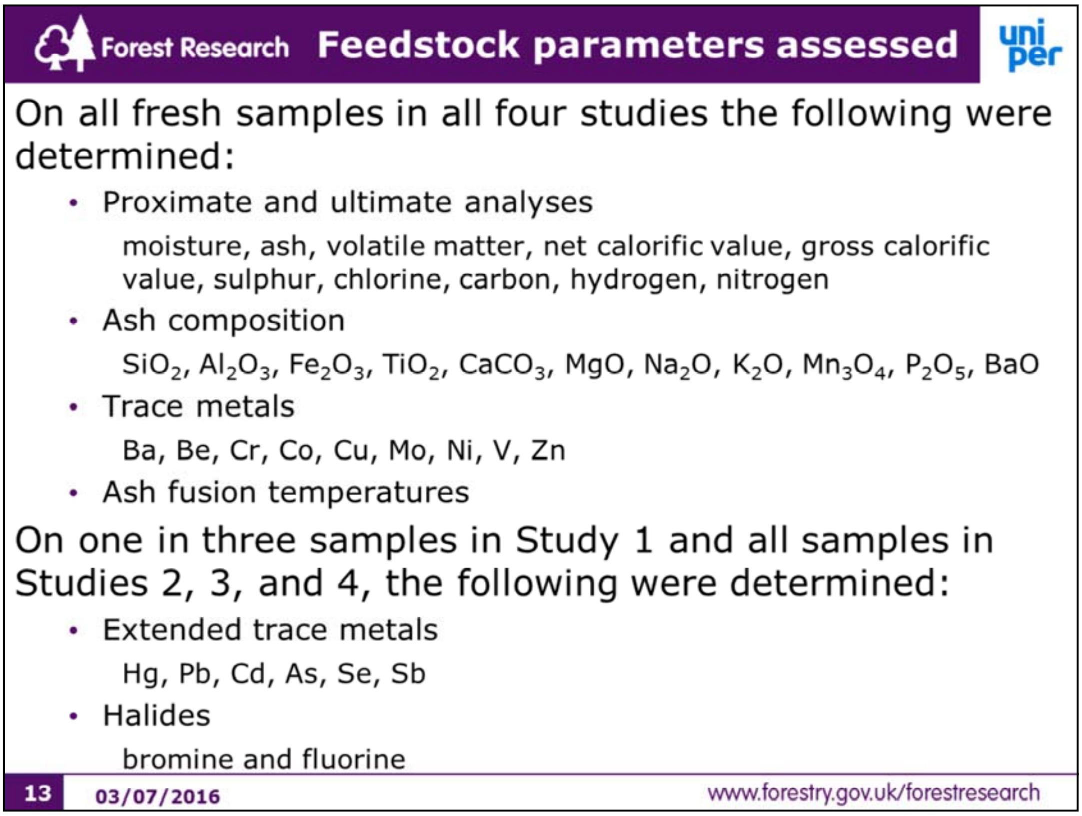
This phase of the project entailed four individual studies, covering:

1. Biomass variability and the factors that influenced it
2. How the variation between samples collected within an individual field compared to that between different fields
3. How the properties of leaves compared to those of other plant parts
4. The effect of pelleting

Only study 1 included all the feedstock types.

SRC = short rotation coppice
SRF = short rotation forest



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Feedstock parameters assessed

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On all fresh samples in all four studies the following were determined:

- 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, $CaCO_3$, MgO, Na_2O, K_2O, Mn_3O_4, P_2O_5, BaO
- Trace metals

  Ba, Be, Cr, Co, Cu, Mo, Ni, V, Zn
- Ash fusion temperatures

On one in three samples in Study 1 and all samples in Studies 2, 3, and 4, the following were determined:

- Extended trace metals

  Hg, Pb, Cd, As, Se, Sb
- Halides

  bromine and fluorine

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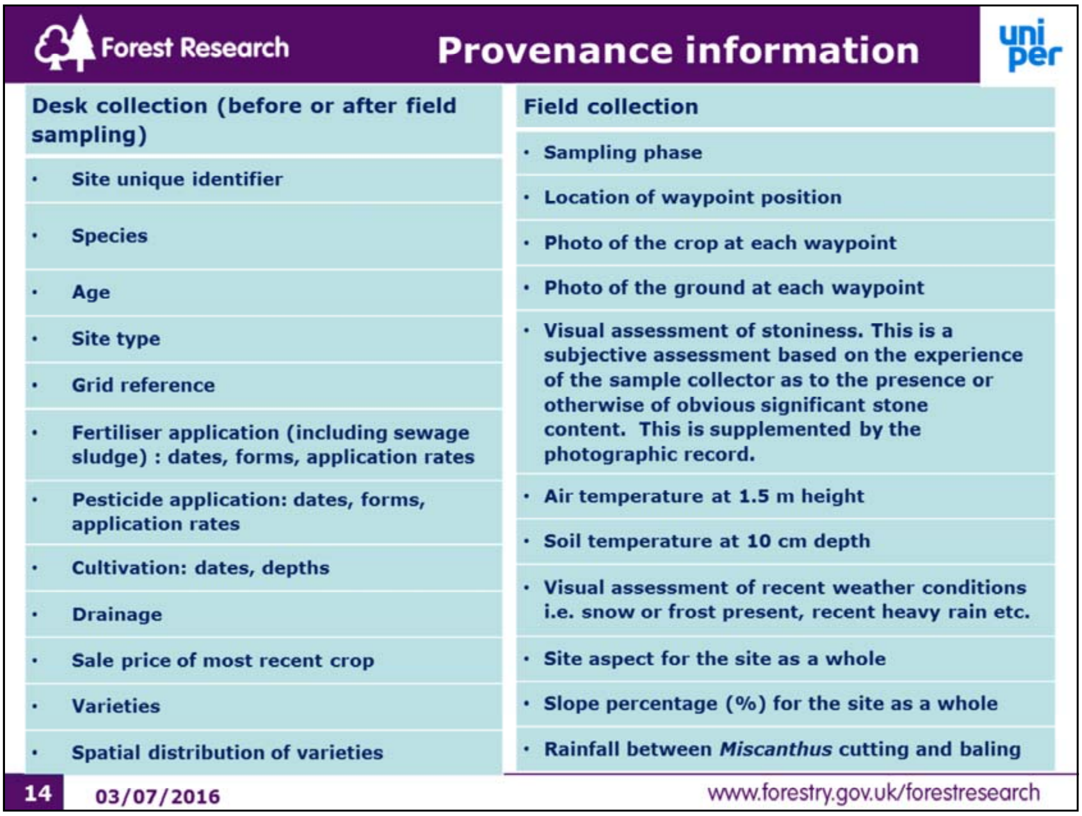
The range of parameters tested covered the range normally assessed for coal and waste wood for comparative purposes. Not all samples were tested for all properties, but this slide lists those tested in all the fresh samples in all four studies.



Provenance information

Desk collection (before or after field sampling)

- Site unique identifier
- Species
- Age
- Site type
- Grid reference
- Fertiliser application (including sewage sludge) : dates, forms, application rates
- Pesticide application: dates, forms, application rates
- Cultivation: dates, depths
- Drainage
- Sale price of most recent crop
- Varieties
- Spatial distribution of varieties

Field collection

- Sampling phase
- Location of waypoint position
- Photo of the crop at each waypoint
- Photo of the ground at each waypoint
- Visual assessment of stoniness. This is a subjective assessment based on the experience of the sample collector as to the presence or otherwise of obvious significant stone content. This is supplemented by the photographic record.
- Air temperature at 1.5 m height
- Soil temperature at 10 cm depth
- Visual assessment of recent weather conditions i.e. snow or frost present, recent heavy rain etc.
- Site aspect for the site as a whole
- Slope percentage (%) for the site as a whole
- Rainfall between *Miscanthus* cutting and baling

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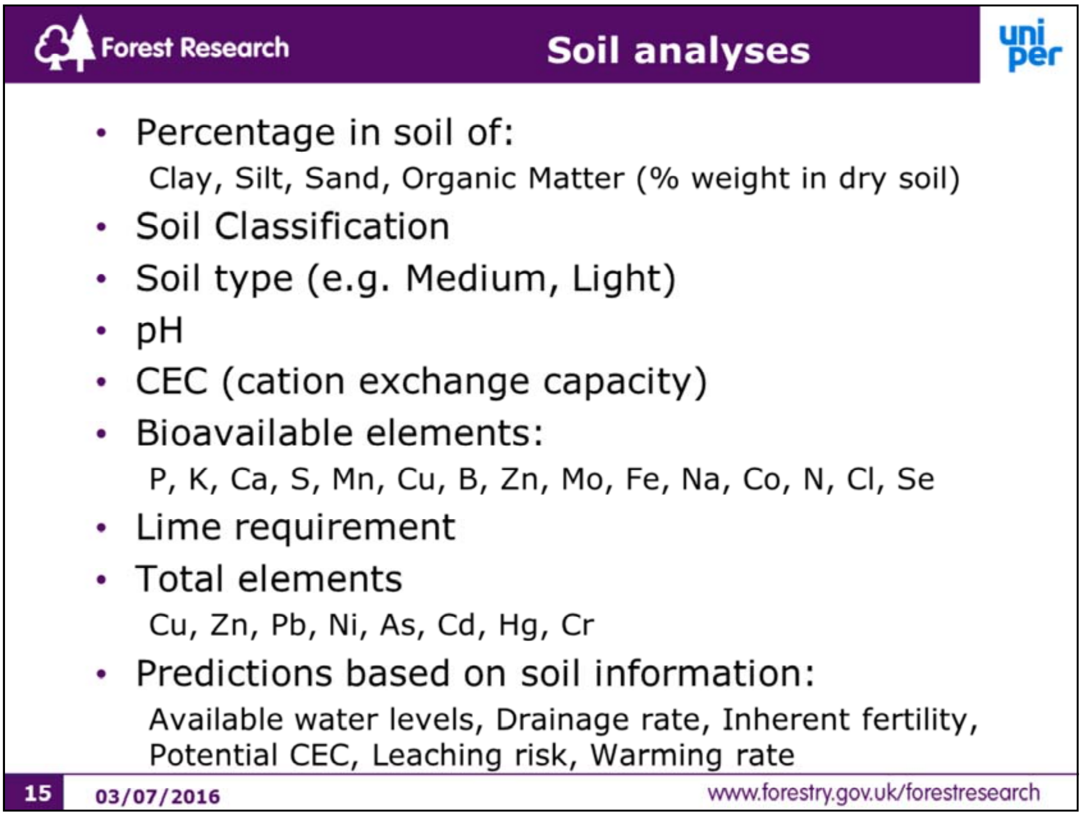
A number of visual observations of the quality of the crop were made, including height/length of crop and the diameter of stems in willow SRC. These can be used, together with the number of stems per ha, as an indication of yield.

Of the supplementary site factors, the angle of slope may be expected to influence the drainage properties of the site. Slope, aspect, exposure to sunshine and wind will impact on potential growth, as will the altitude of the site. The stoniness will influence drainage properties, availability of minerals and root growth.

Of the management factors, fertilizer application in combination with natural soil fertility will influence nutrient availability to the growing plant, and hence growth rates; if the input is in the form of sewage sludge it is possible that it may also contain elevated levels of heavy metals and other minerals not usually present.

Observations of the crop itself give an additional insight into the overall state of the crop and an indication of yield.

Factors, such as precise date of harvest, and time between cutting and baling (*Miscanthus* specifically), were very much dictated by weather and site conditions, contractor availability, etc. Samples were taken within 24 hours of the harvest/baling, and the dates recorded.



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Soil analyses

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- Percentage in soil of:
  Clay, Silt, Sand, Organic Matter (% weight in dry soil)
- Soil Classification
- Soil type (e.g. Medium, Light)
- pH
- CEC (cation exchange capacity)
- Bioavailable 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 CEC, Leaching risk, Warming rate

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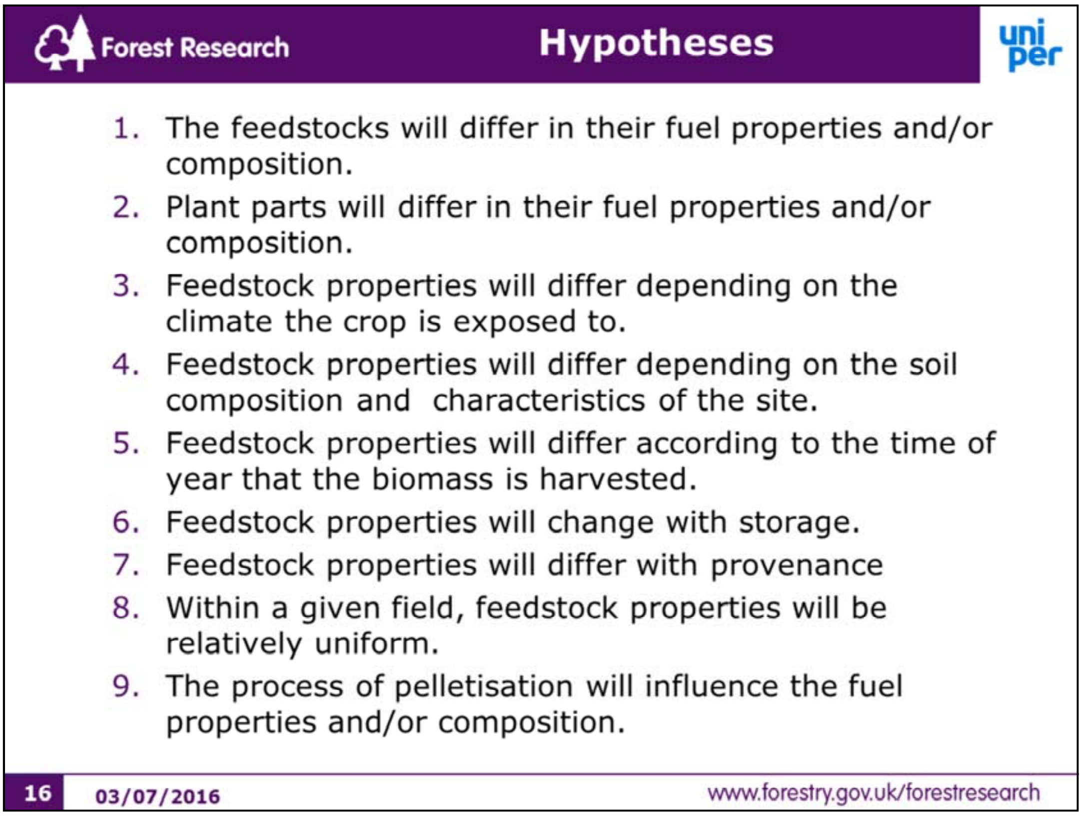
In addition to analyzing the feedstock samples, soil samples were taken from each site and analyzed for a range of physical and chemical parameters so they could be compared with the feedstock samples from that site.



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Hypotheses

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1. The feedstocks will differ in their fuel properties and/or composition.
2. 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 change with storage.
7. Feedstock properties will differ with provenance
8. Within a given field, feedstock properties will be relatively uniform.
9. The process of pelletisation will influence the fuel properties and/or composition.

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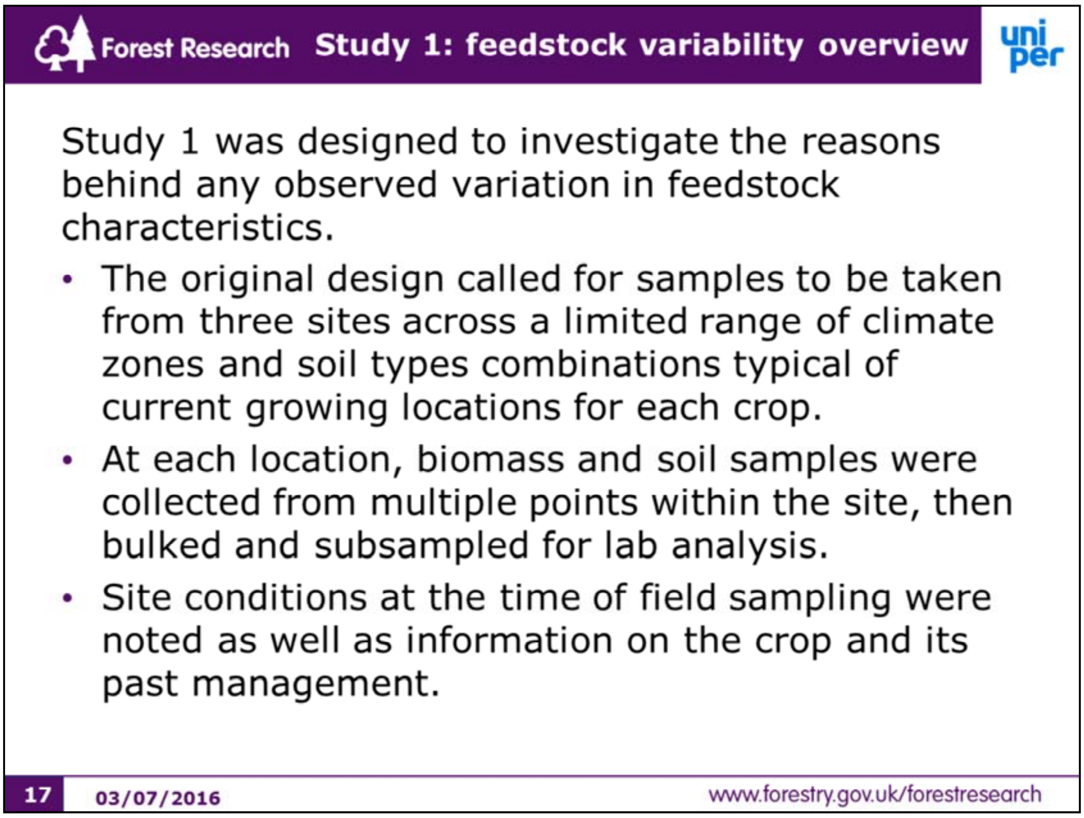
A series of hypotheses was drawn up for the expected relationships between feedstock parameters and variables such as site properties, plant part, time of year, storage, provenance information etc., which were then tested against observed results.

Additional information justifying Hypothesis 1 and 2.

- H1: The feedstocks examined range from a grass (*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).
- H2: With the exception of the *Miscanthus,* the feedstocks are differentiated into plant parts that have different functions



Study 1: feedstock variability overview

Study 1 was designed to investigate the reasons behind any observed variation in feedstock characteristics.

- The original design called for samples to be taken from three sites across a limited range of climate zones and soil types combinations typical of current growing locations for each crop.
- 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.

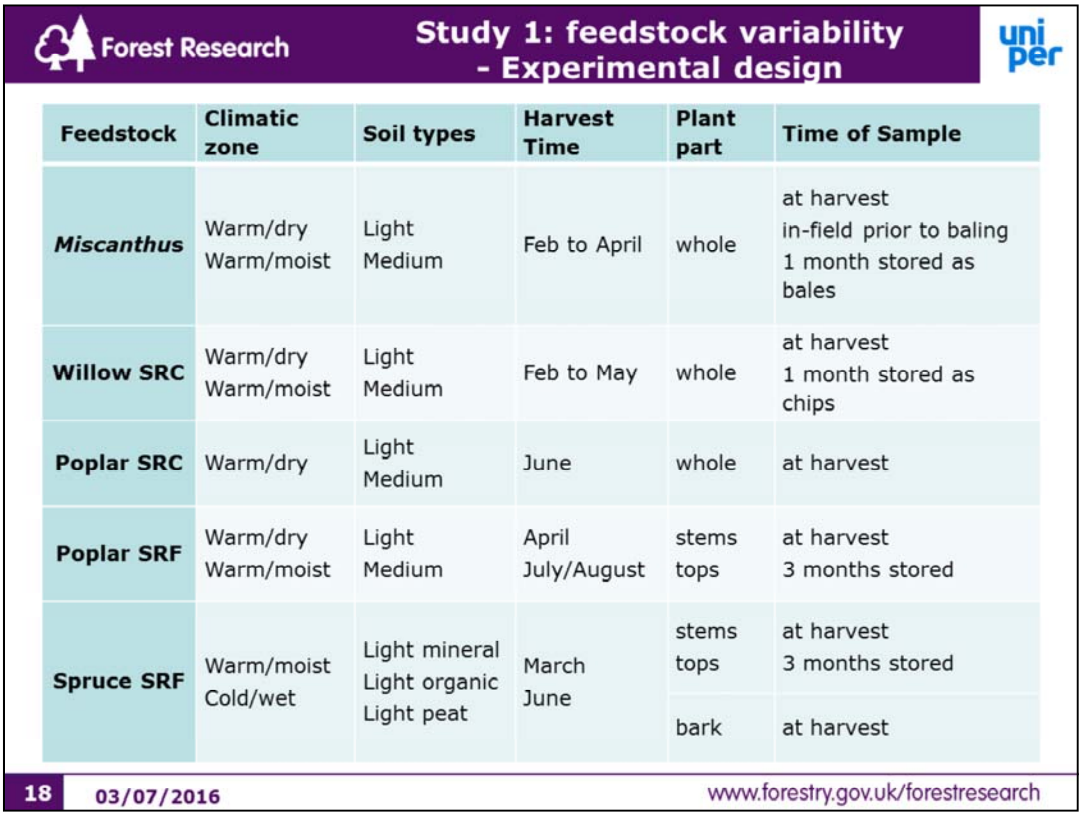
Study 1 was the primary study to measure a range of physical and chemical properties of biomass feedstocks, measure the variation in those properties between samples, and investigate the reasons behind the observed variations.

In order to assess the impact of various site issues, such as climate and soil type, sites were chosen based on GIS information.

The original study design included sample collection from three different locations in each combination of climate zone and soil type but in practice this was not always achieved for reasons including:

- insufficient sites were available for some combinations
- the actual soil types were generally different from the GIS predicted soil type

As a result, for *Miscanthus,* willow SRC, poplar SRC and poplar SRF only two soil types (Medium and Light) were included in the study with no representatives of Heavy soils.



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Study 1: feedstock variability - Experimental design

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Feedstock	Climatic zone	Soil types	Harvest Time	Plant part	Time of Sample
Miscanthus	Warm/dry Warm/moist	Light Medium	Feb to April	whole	at harvest in-field prior to baling 1 month stored as bales
Willow SRC	Warm/dry Warm/moist	Light Medium	Feb 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	stems tops	at harvest 3 months stored
Spruce SRF	Warm/moist Cold/wet	Light mineral Light organic Light peat	March June	stems tops	at harvest 3 months stored
				bark	at harvest

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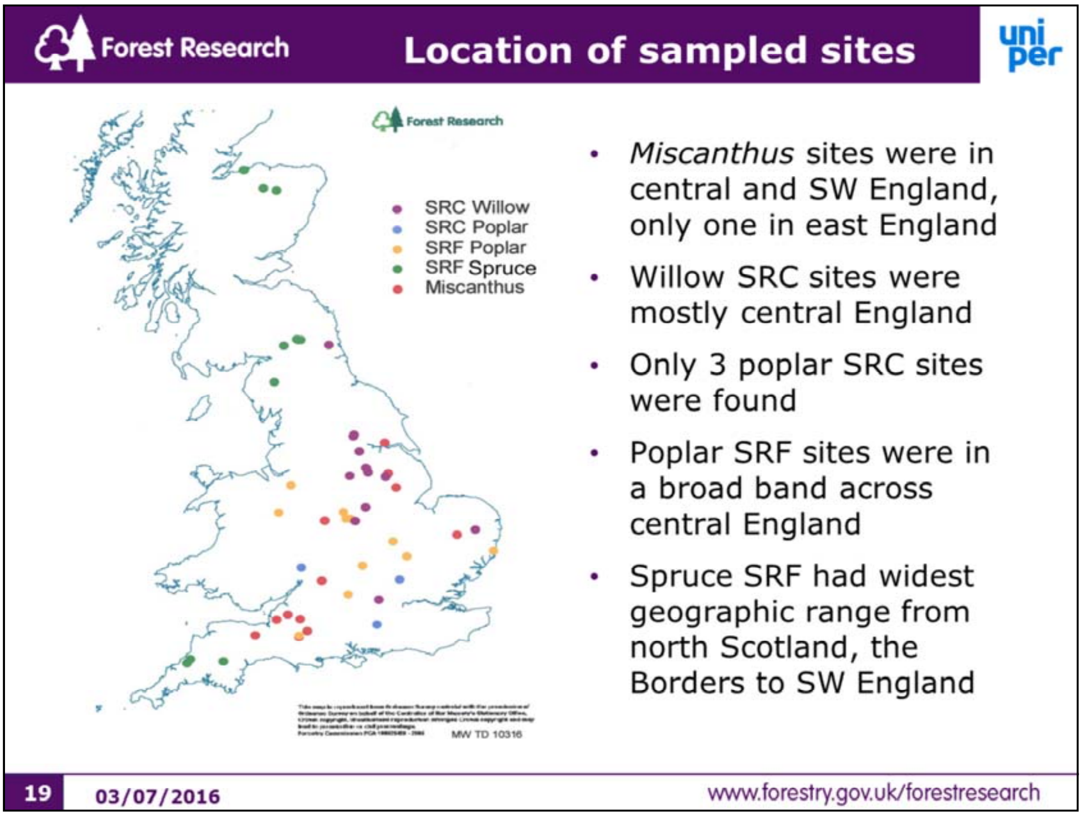
The rationale for investigating these factors is outlined in the notes of this and the next slide.

Soil type. The soil fertility, including available nitrogen, phosphorus and potassium (NPK) and other mineral content, influences the availability of these nutrients to the growing plant. Soil physical characteristics (including organic matter content and particle size distribution) influence the water retention and draining properties and the soil’s ability to warm up quickly or slowly and retain or lose heat. All these factors may be expected to influence growth rate and biomass allocation within the plant, e.g. to stems, branches, roots and leaves; soil characteristics therefore influence ash content, and also wood density. If soil compaction or stone content are excessive, the rooting of plants can be severely hindered causing restrictions on root growth and possibly instability. In addition, the presence of primary minerals and trace elements is expected to influence the extent to which these are found in the harvested biomass.

Harvest time. For a particular site, plant properties will vary seasonally with senescence in autumn, dormancy over winter, release of dormancy in spring, followed by leaf and shoot extension during late spring and summer. Seasonal changes are especially marked in deciduous species. Consequently time of harvesting is expected to have a significant impact on biomass feedstock properties.

Plant part. Many of the key crop attributes vary within the plant and frequently differ in woody plants cf. grasses, therefore the choice of which plant parts to sample depends on the species and the distribution of key attributes.



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Location of sampled sites

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- *Miscanthus* sites were in central and SW England, only one in east England
- Willow SRC sites were mostly central England
- Only 3 poplar SRC sites were found
- Poplar SRF sites were in a broad band across central England
- Spruce SRF had widest geographic range from north Scotland, the Borders to SW England

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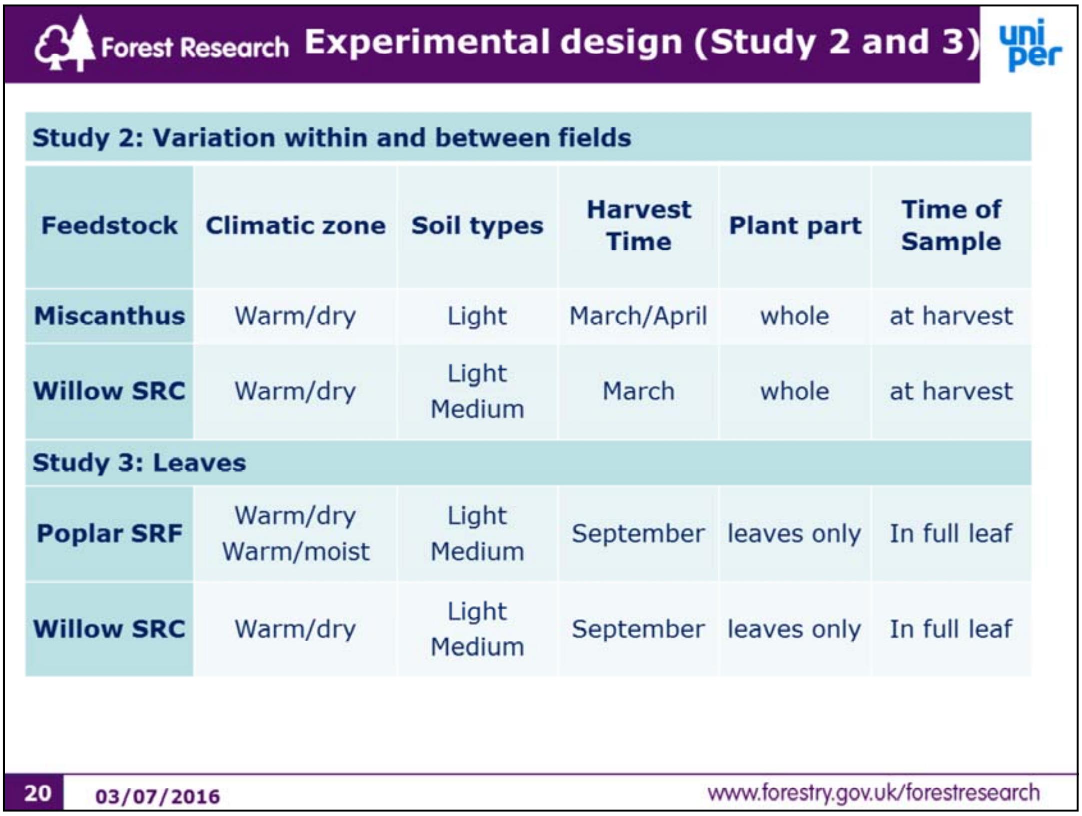
Climate zone. The rate of growth obviously influences yield and also properties of significance to utilisation and conversion such as wood density. Local rainfall, temperatures and sunshine are likely to influence growth rate hence wood density. Larger stem and branch diameter tends to reduce the relative proportion of bark, and is consequently likely to reduce ash content, so factors that promote more rapid growth may be expected to influence ash content.



Forest Research **Experimental design (Study 2 and 3)** uniper

Feedstock	Climatic zone	Soil types	Harvest Time	Plant part	Time of Sample
Study 2: Variation within and between fields					
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	September	leaves only	In full leaf
Willow SRC	Warm/dry	Light Medium	September	leaves only	In full leaf

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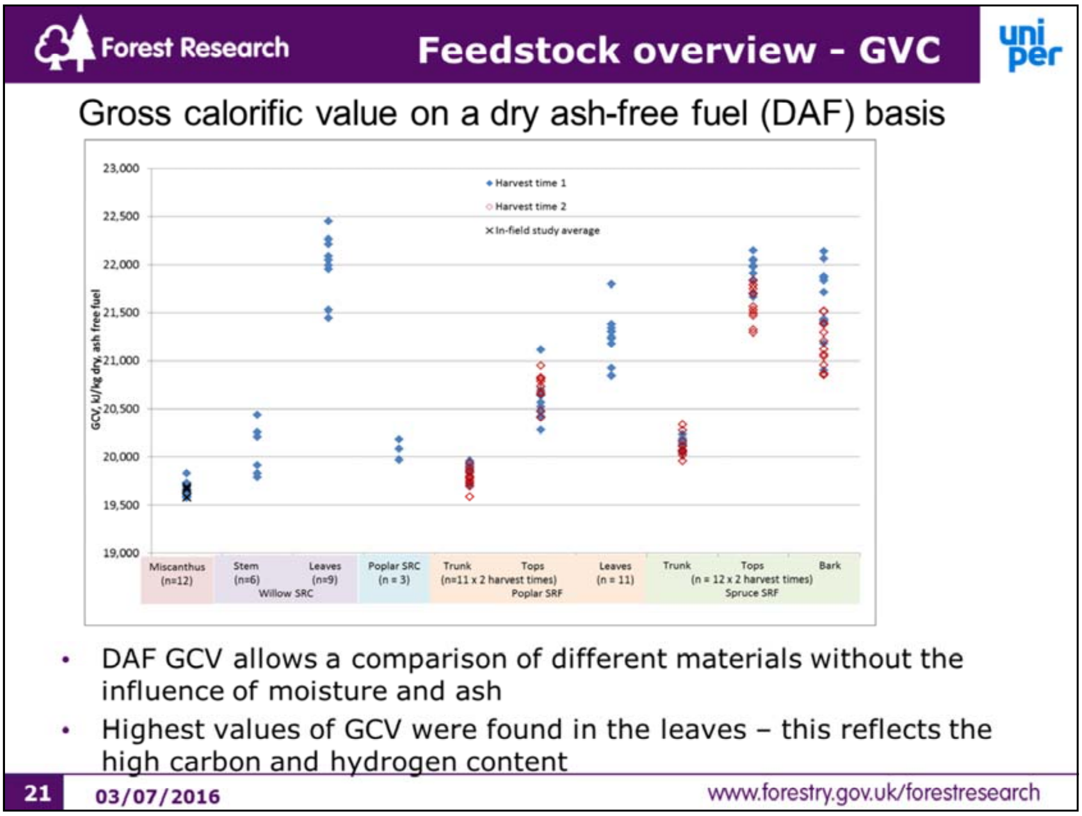
In addition to the large Study 1 (described in slide 18), three smaller studies explored specific supplementary points:

Study 2 investigated feedstock variability within a site (*Miscanthus* and one variety of willow SRC only) addressing Hypothesis 8. 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 only) 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 9. 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 biomass sampled within the project.



Feedstock overview - GVC

Gross calorific value on a dry ash-free fuel (DAF) basis

- DAF GCV allows a comparison of different materials without the influence of moisture and ash
- Highest values of GCV were found in the leaves – this reflects the high carbon and hydrogen content

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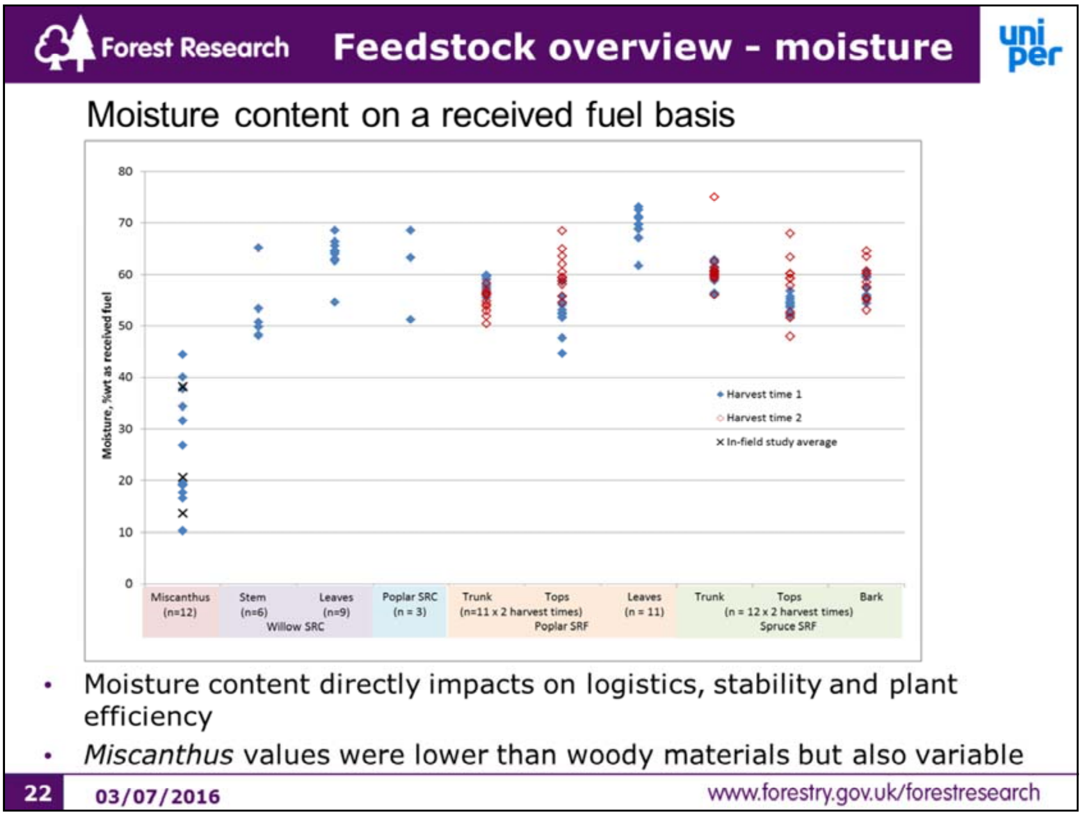
The following slides summarise the most important findings from Studies 1, 2 and 3 by feedstock and plant part and illustrate the impact of species and where applicable, plant part and harvest time.

This figure illustrates the changes in DAF GCV between the different feedstocks and parts of feedstock. The DAF GCV was lowest for the *Miscanthus*, the stems of willow SRC and 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 stems (lower) wood and *Miscanthus*. 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.



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Feedstock overview - moisture

Moisture content on a received fuel basis

- Moisture content directly impacts on logistics, stability and plant efficiency
- *Miscanthus* values were lower than woody materials but also variable

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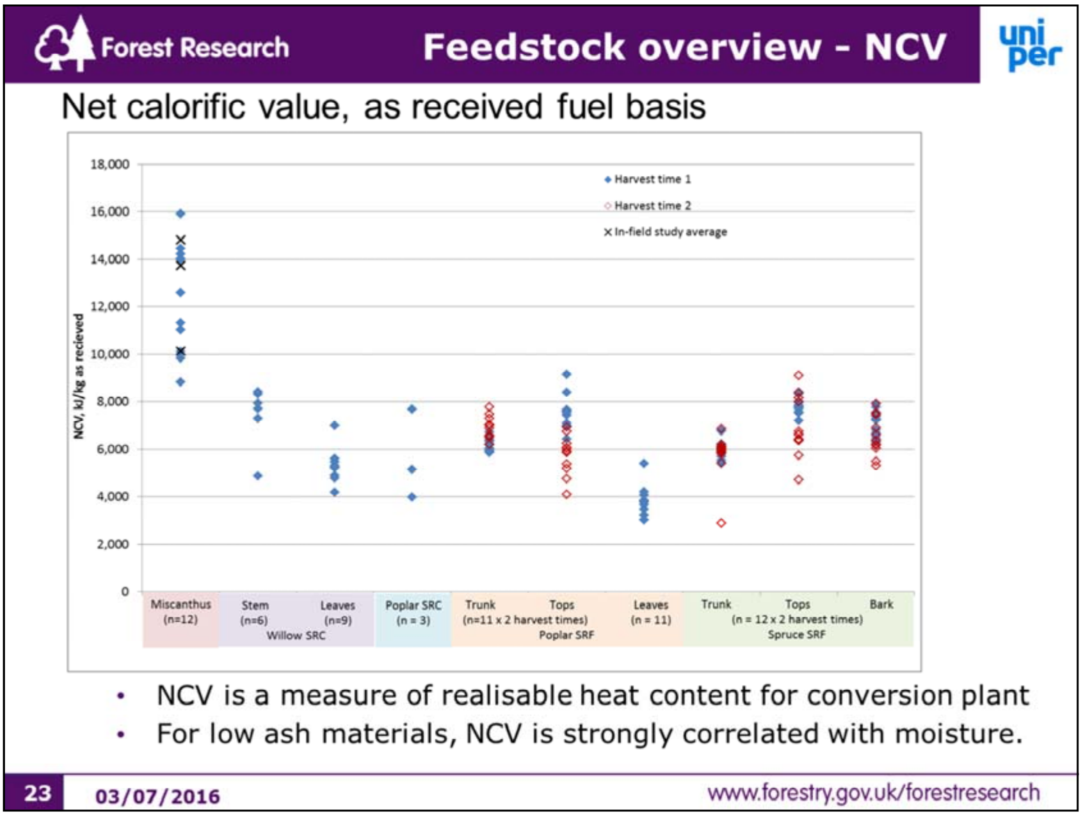
Here we see the large variation in moisture content between the freshly harvested feedstocks.

Miscanthus had the lowest and most variable moisture content as harvested (possibly due to the material being more susceptible than the woody feedstocks to absorbing and losing moisture according to the conditions at harvest). The stems (lower) wood and tops contained typically 50-60% moisture with the leaves containing >60% moisture.

The realisable heat content (NCV) is strongly correlated with moisture content (see next slide).



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Feedstock overview - NCV

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Net calorific value, as received fuel basis

- NCV is a measure of realisable heat content for conversion plant
- For low ash materials, NCV is strongly correlated with moisture.

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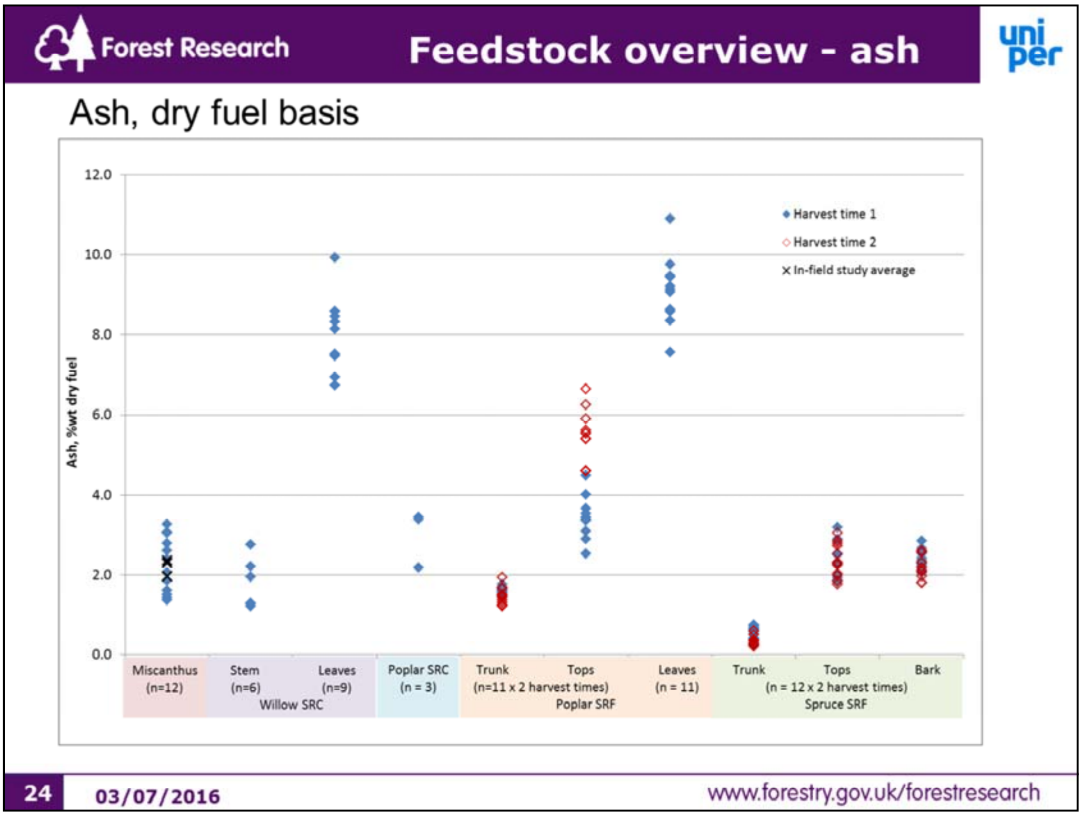
The NCV of *Miscanthus* was generally highest but was also very variable. For the woody biomass, the NCV was broadly similar for the different plant parts but in the case of both willow SRC and poplar the NCV of leaves tended to be lower than for the woodier parts of the plant.



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Feedstock overview - ash

Ash, dry fuel basis

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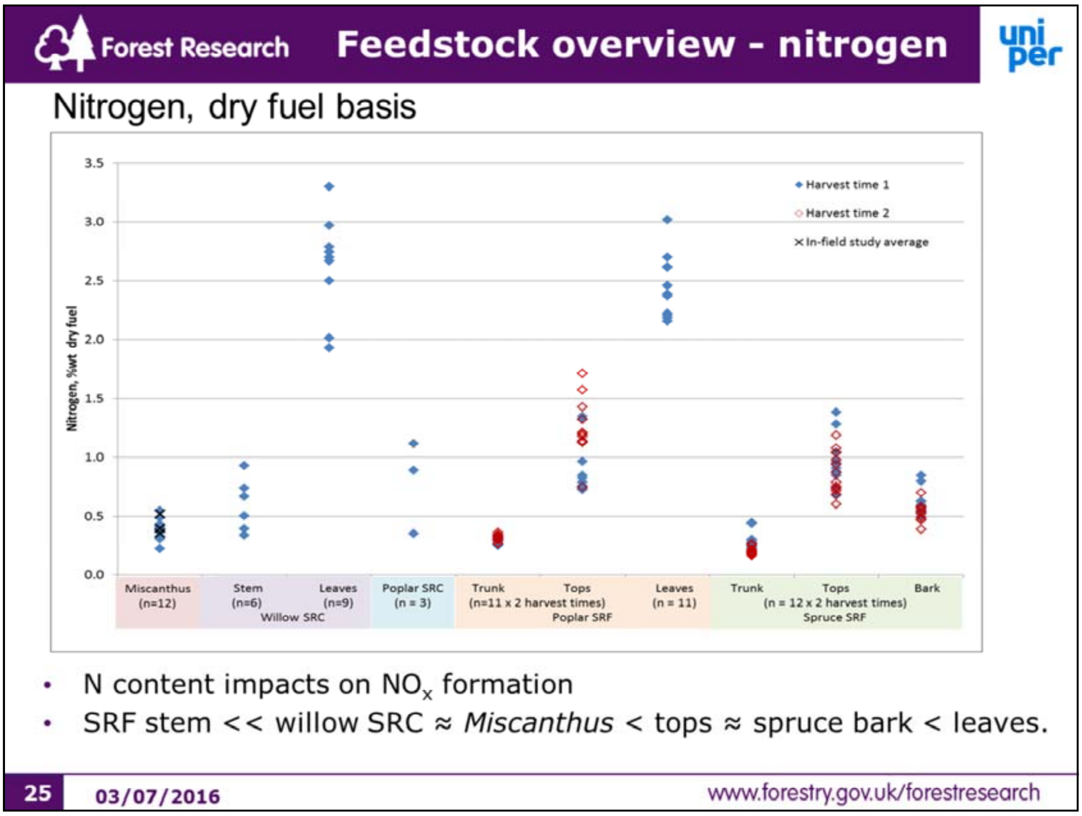
This figure clearly shows the very low ash levels in the stems of the woody biomass of <2%, which increased in the tops up to 6%, with the leaves containing the highest levels at up to 10% ash (dry). The dry ash content of the spruce SRF bark was comparable with that in the spruce SRF tops at 2-3% and its removal from the stem samples contributes to the very low value here. The poplar SRF stem samples, in contrast, were analysed with the bark attached. The *Miscanthus* dry ash content was comparable with that in the tops of the woody biomass types.

There was an obvious increase in the ash of the poplar SRF tops sampled in July/August compared to three months earlier in April corresponding to increased leaf content. The effect of harvest time on the ash of the tops of the coniferous species was much less marked which is consistent with the fact that needles were present at both sampling times.



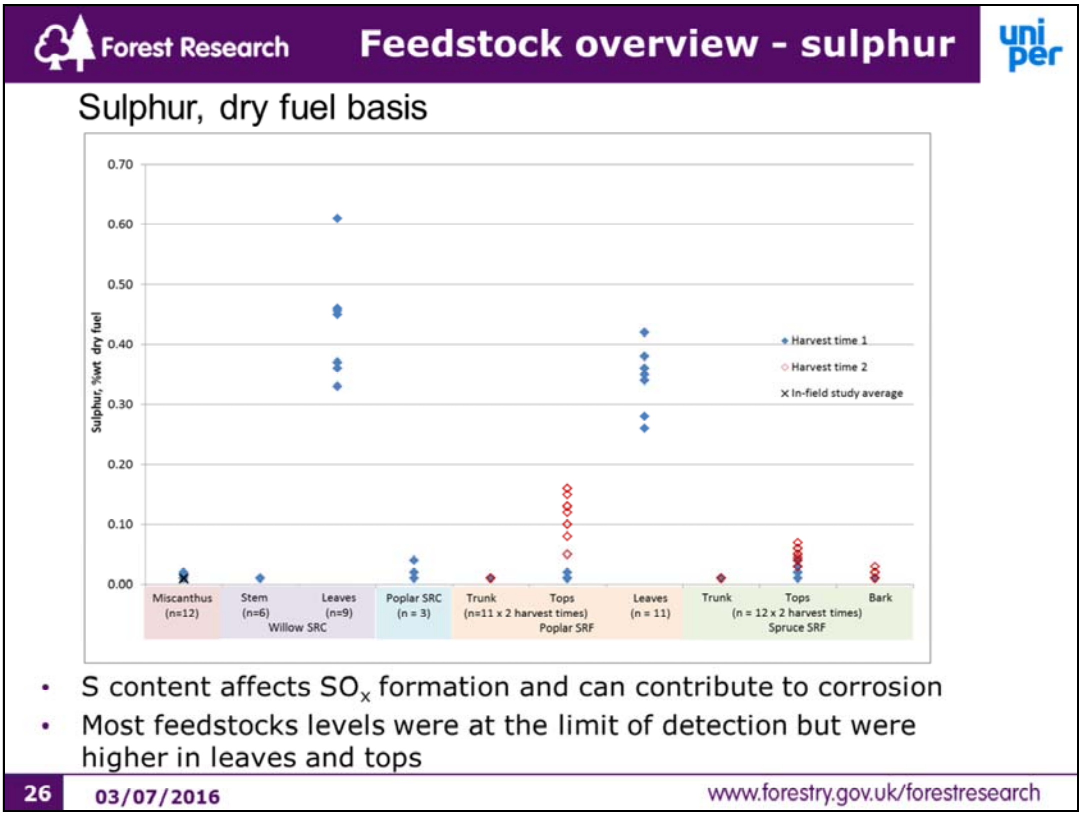
Feedstock overview - nitrogen

Nitrogen, dry fuel basis

- N content impacts on NO_x formation
- SRF stem << willow SRC ≈ *Miscanthus* < tops ≈ spruce bark < leaves.

Nitrogen concentrations in feedstocks will impact on the environmental performance of the subsequent combustion process, contributing to fuel NOx. In general lower concentrations in the feedstock are preferable from this perspective.

The dry nitrogen content of the feedstocks is shown above. In broad terms the pattern of variation in nitrogen was similar to ash. The lowest nitrogen contents were found in the stems 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 stems, with the spruce tops ranging from 0.6-1.4% N, with the bark lower at 0.4-0.8% N. The poplar SRF was generally higher in nitrogen than the equivalent spruce samples, with the level in the tops from the second harvest significantly higher than the first. 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 stems, the second harvest does generally show higher nitrogen than the first for the poplar SRF tops. Levels of nitrogen in the *Miscanthus* were similar to those of the spruce SRF tops and bark.



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Feedstock overview - sulphur

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Sulphur, dry fuel basis

- S content affects SO_x formation and can contribute to corrosion
- Most feedstocks levels were at the limit of detection but were higher in leaves and tops

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Sulphur concentrations in feedstocks affect the environmental performance of the subsequent combustion process, and in general lower concentrations in the feedstock are preferable from this perspective.

Again the leaves contained the highest levels (up to 0.6% dry) with the remaining feedstocks and plant parts generally containing <0.1% (dry). The stems always contained the lowest levels (the stem samples being at or below the limit of detection of 0.01%). 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.

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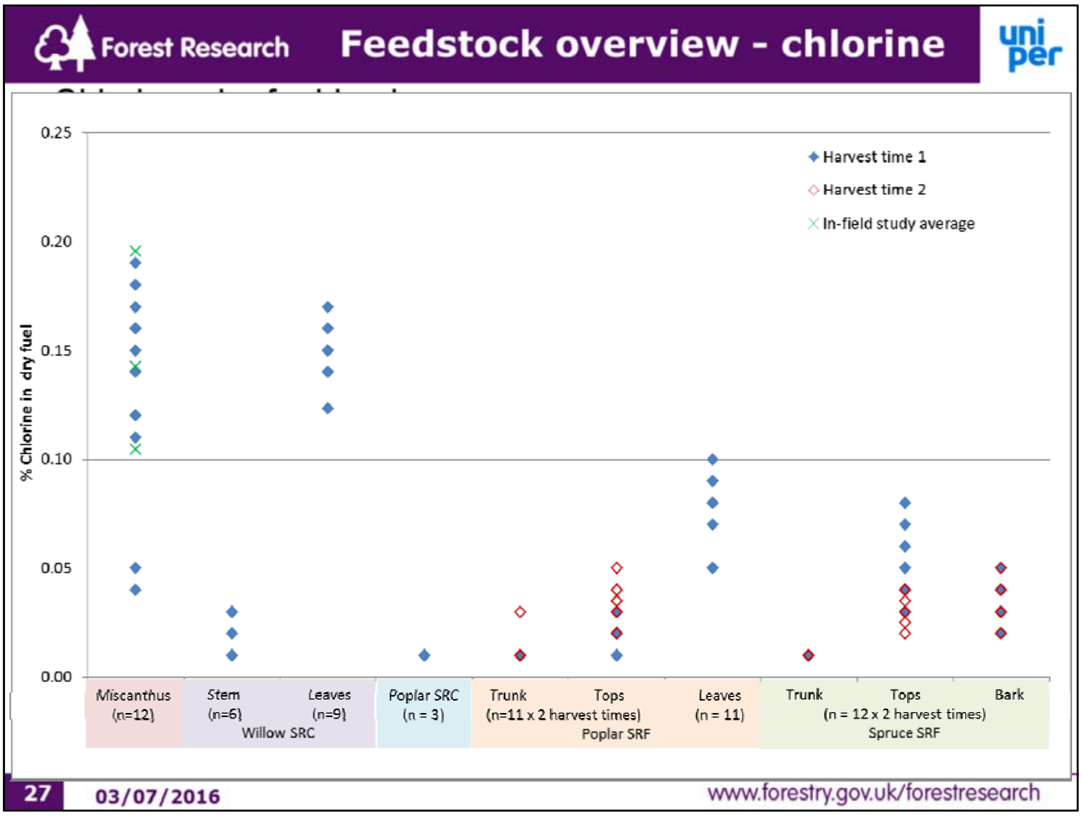
Feedstock overview - chlorine



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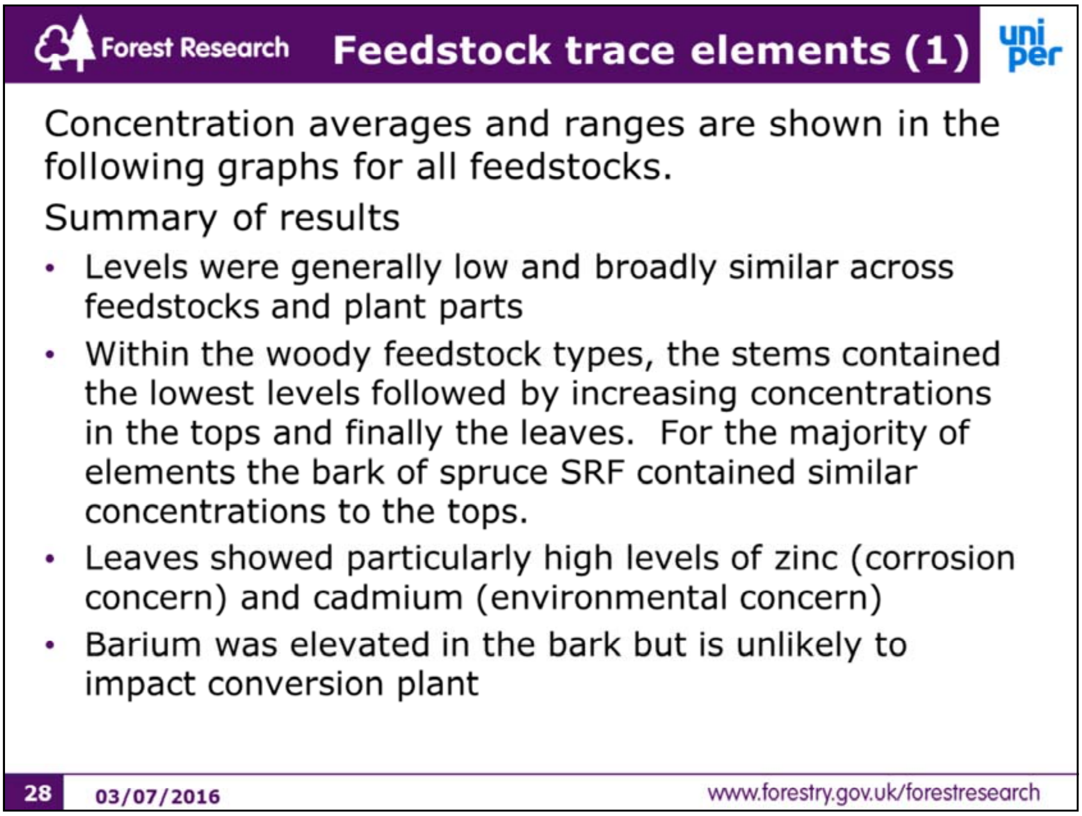
Chlorine concentrations in feedstocks will impact on the environmental performance of the subsequent combustion process, and in general lower concentrations in the feedstock are preferable from this perspective. Chlorine also can play a role in corrosion mechanisms, particularly in combination with alkali metals such as potassium.

Miscanthus clearly contained the highest levels and were very variable. The willow SRC leaves contained markedly higher levels of chlorine than those from the poplar SRF leaves. The stems generally contained chlorine levels that were lower than the limit of analytical detection of 0.01%.



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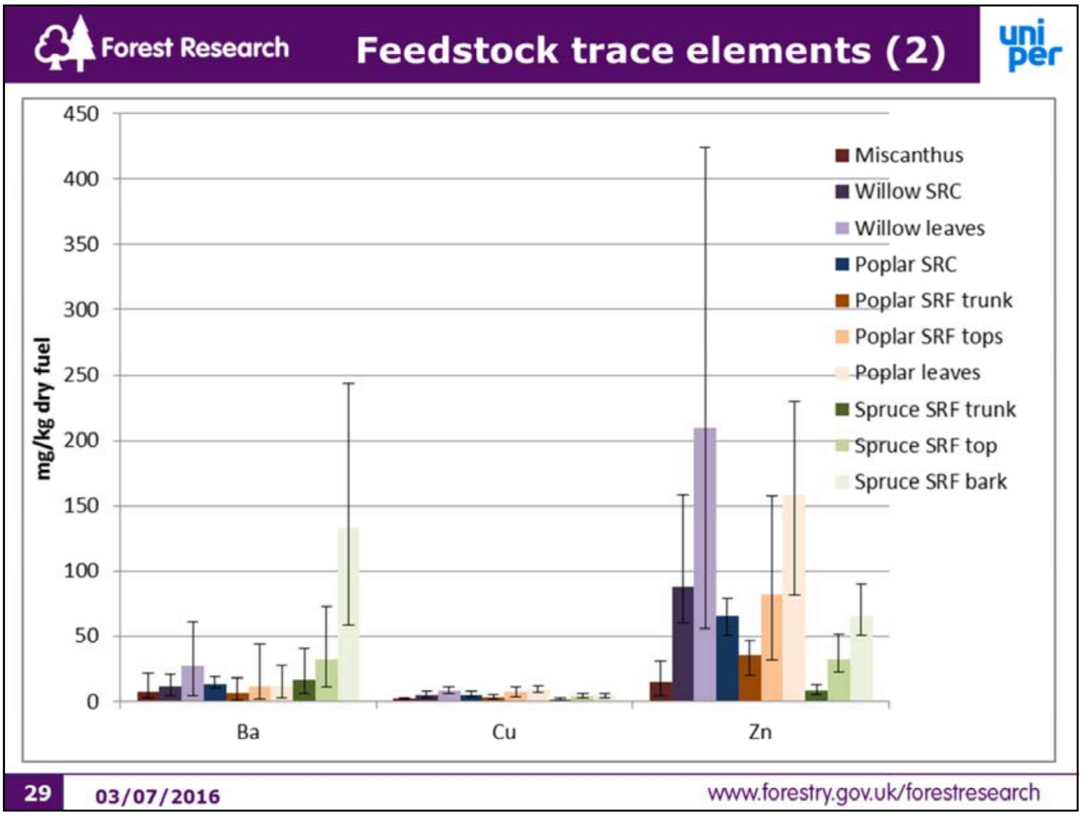
Feedstock trace elements (1)

Concentration averages and ranges are shown in the following graphs for all feedstocks.

Summary of results

- Levels were generally low and broadly similar across feedstocks and plant parts
- Within the woody feedstock types, the stems 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 (corrosion concern) and cadmium (environmental concern)
- Barium was elevated in the bark but is unlikely to impact conversion plant

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.



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Feedstock trace elements (2)

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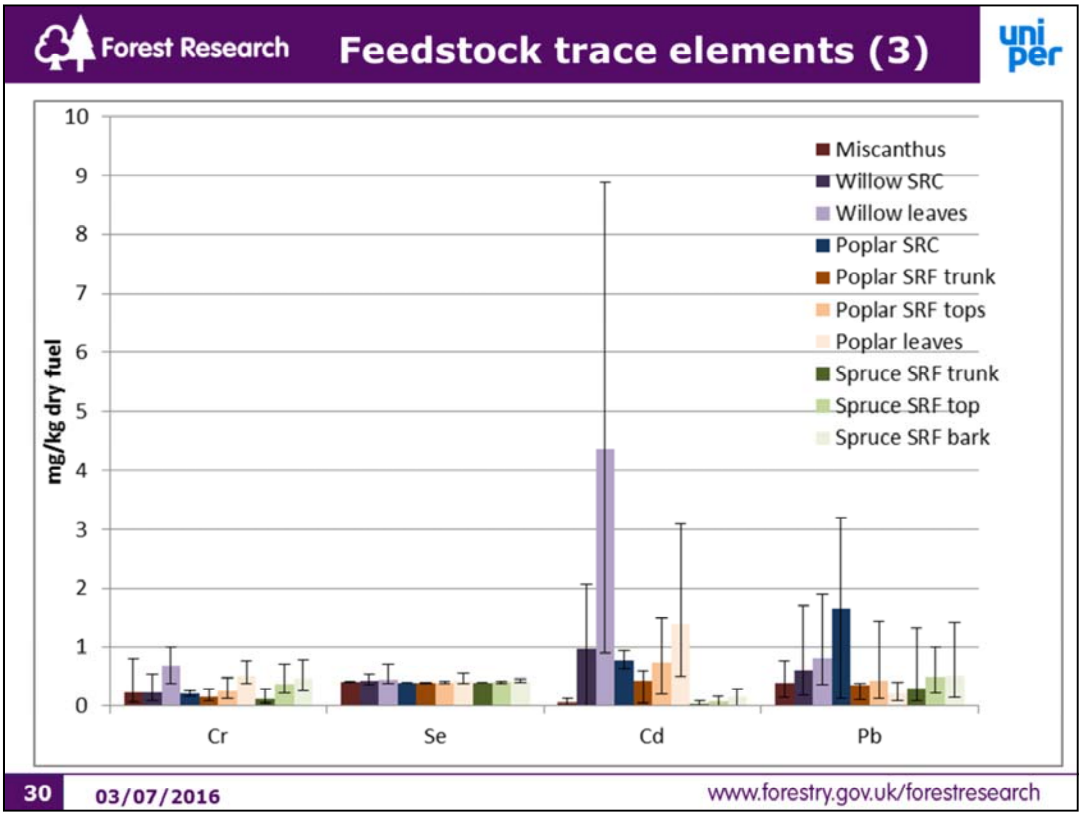
This and the next slide show the average trace element contents of the fresh feedstocks (harvest time is not differentiated in these graphs), with the range of the data indicated by the bars on each column. Note that those values deemed to be outliers for statistical analysis have been excluded from 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.

As explained in the previous slide within the woody feedstock types the stems contain 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.

The following notable points are given as examples:

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.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Feedstock trace elements (3)

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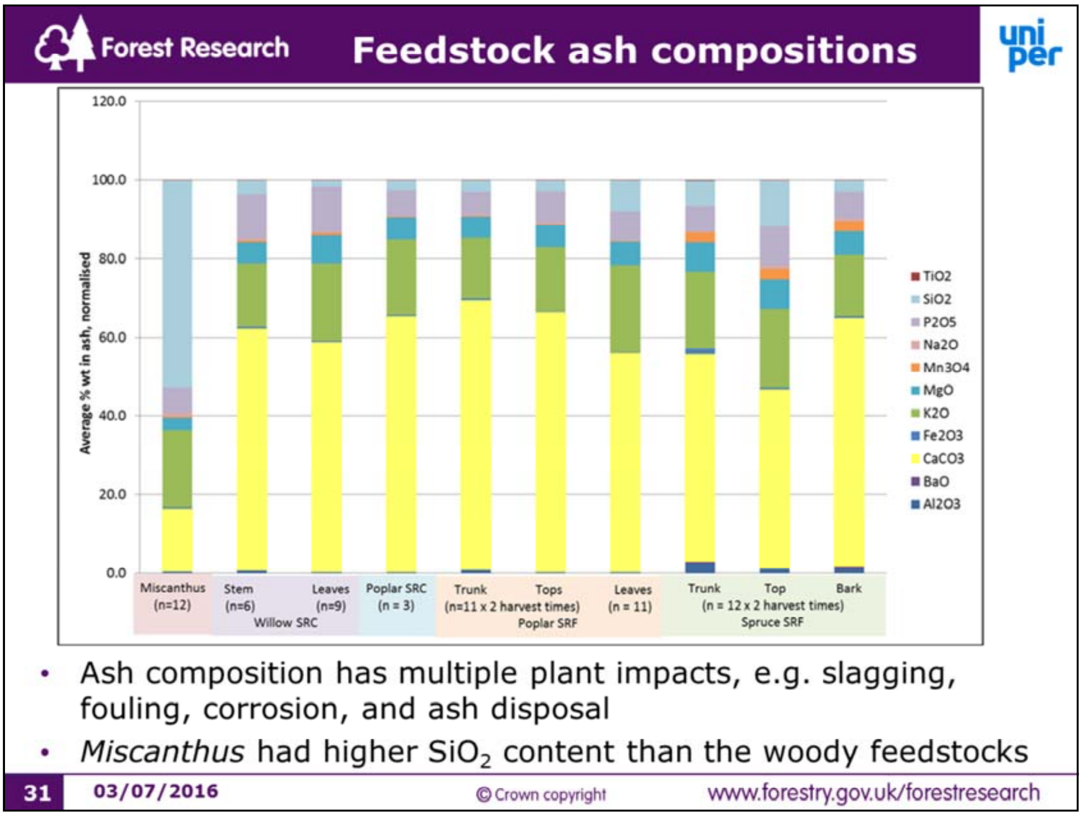
Cadmium – Levels in the willow leaves in particular were high and variable (comparable to those in some waste woods). All of the broadleaf samples were higher in cadmium than either the spruce or *Miscanthus* samples. Cadmium is primarily of concern as an environmental pollutant.

Lead – while the poplar SRC appeared to be higher in lead than the other feedstocks, this was 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 is implicated in some corrosion mechanisms, but the levels seen in the feedstocks in this study were 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.



Feedstock ash compositions

- Ash composition has multiple plant impacts, e.g. slagging, fouling, corrosion, and ash disposal
- *Miscanthus* had higher SiO_2 content than the woody feedstocks

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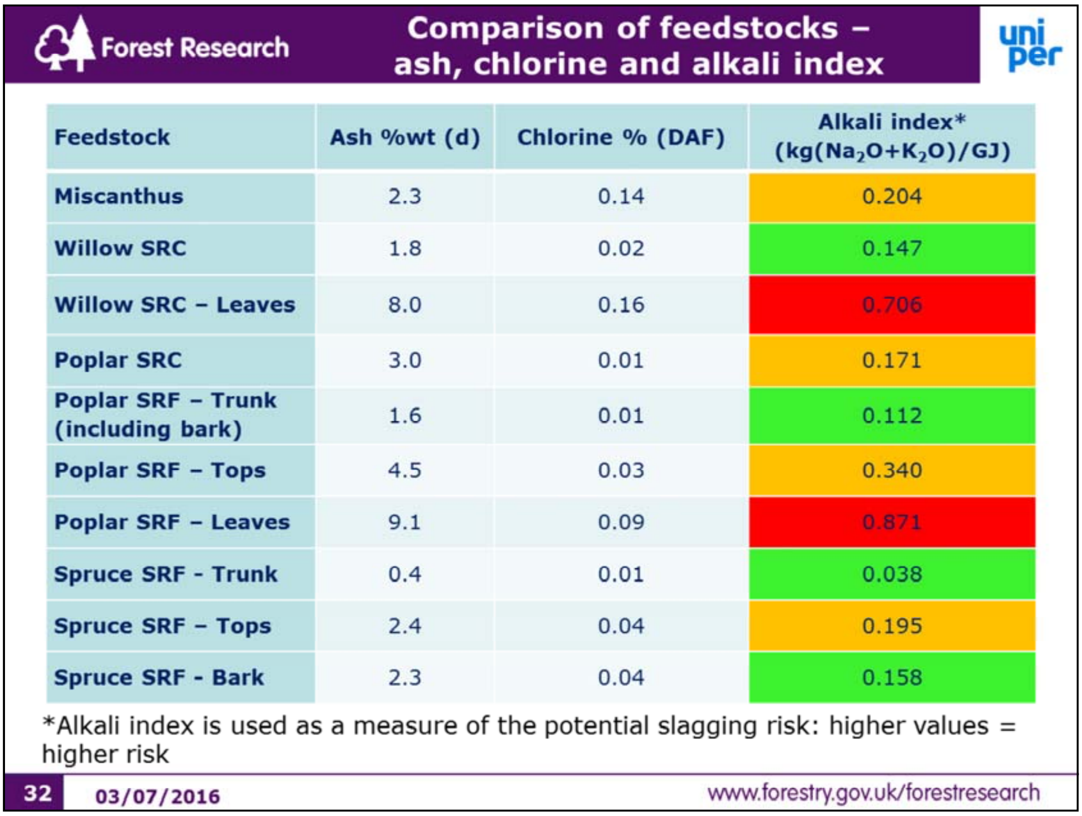
The ash composition will influence a number of operational concerns within the plant, including slagging, fouling, corrosion, erosion, bed agglomeration in fluidised bed systems, emissions (particularly of acidic gases) and ash disposal/recovery options.

With the exception of the *Miscanthus*, all of the feedstock ashes were predominantly composed of calcium carbonate; potassium oxide levels were 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* samples contained significant levels of silica. A potential cause of high silica could be as a result of contamination by soil, however *Miscanthus,* and similar grassy crops (such as cereal straw) are known to contain high levels of silica. Because the silica was consistently high, these values are likely to be accurate measurements of the levels in *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.



Comparison of feedstocks – ash, chlorine and alkali index

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 (including bark)	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

*Alkali index is used as a measure of the potential slagging risk: higher values = higher risk

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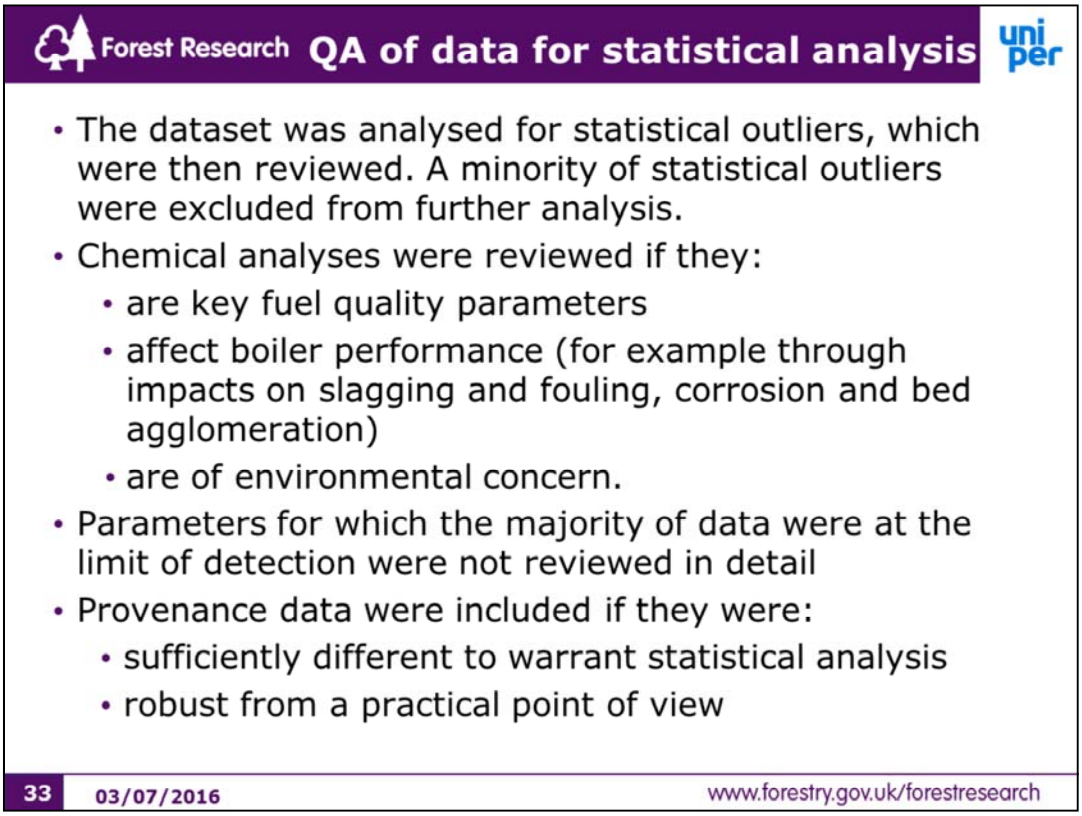
One index that appears to be effective for predicting slagging behaviour in biomass systems is the alkali index, which is based on the alkali mass input per unit energy. Values below 0.17 indicate a low fouling/slagging risk, for those between 0.17 and 0.34 fouling/slagging is considered to be probable and above 0.34 fouling/slagging is certain. As the alkali index is often included in boiler fuel specifications, it has been calculated for the feedstocks in this project.

The comparison above of equivalent plant parts for the poplar and spruce SRF demonstrates that the spruce samples were nearly always lower in ash and chlorine, though it is important to remember that the spruce SRF trunk samples were analysed with bark removed.

The high alkali index of willow and poplar leaves suggested potential for slagging and fouling.

The levels of ash, chlorine content and calculated alkali index for the *Miscanthus* samples were also interesting to compare against the other data in the 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 not always justified.



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QA of data for statistical analysis

- The dataset was analysed for statistical outliers, which were then reviewed. A minority of statistical outliers were excluded from further analysis.
- Chemical analyses were reviewed if they:
  - are key fuel quality parameters
  - affect boiler performance (for example through impacts on slagging and fouling, corrosion and bed agglomeration)
  - are of environmental concern.
- Parameters for which the majority of data were at the limit of detection were not reviewed in detail
- Provenance data were included if they were:
  - sufficiently different to warrant statistical analysis
  - robust from a practical point of view

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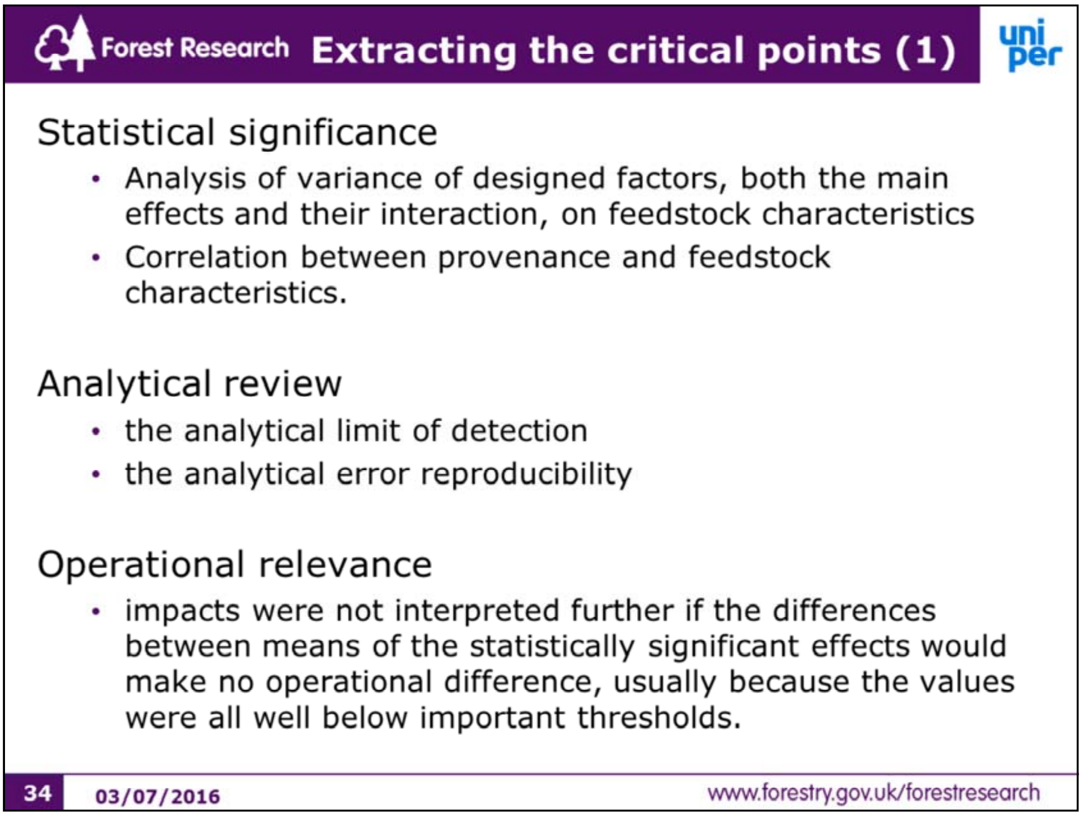
The four studies generated a very large dataset (4 MB) so it was critical to develop a transparent, consistent approach to selecting the key data for detailed analysis and consideration.



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Extracting the critical points (1)

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Statistical significance

- Analysis of variance of designed factors, both the main effects and their interaction, on feedstock characteristics
- Correlation between provenance and feedstock characteristics.

Analytical review

- the analytical limit of detection
- the analytical error reproducibility

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.

Statistical significance

For the analysis of structured effects, which are also referred to as designed factors, e.g. climate zone, harvest time, storage duration and soil type, by ANOVA (ANalysis Of VAriance) or REML (REsidual Maximum Likelihood) : effects with a probability of > 1 in 20 of occurring by chance alone were not investigated further.

For Correlations: if the variation in the soil or provenance explained <50% of the variation in the feedstock characteristic the correlation was not considered further.

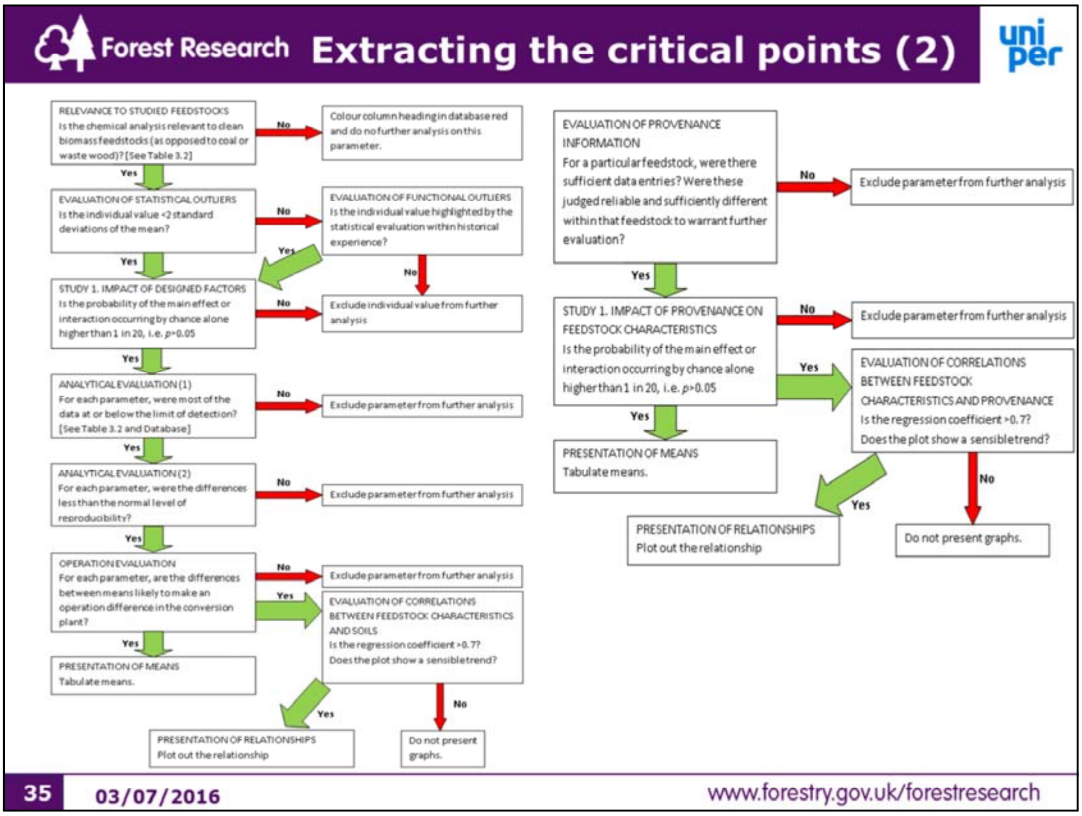
Analytical significance

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.

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).

Operational significance

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.



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Extracting the critical points (2)

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RELEVANCE TO STUDIED FEEDSTOCKS
Is the chemical analysis relevant to clean biomass feedstocks (as opposed to coal or waste wood)? [See Table 3.2]

Colour column heading in database red and do no further analysis on this parameter.

EVALUATION OF STATISTICAL OUTLIERS
Is the individual value <2 standard deviations of the mean?

EVALUATION OF FUNCTIONAL OUTLIERS
Is the individual value highlighted by the statistical evaluation within historical experience?

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

Exclude individual value from further analysis

ANALYTICAL EVALUATION (1)
For each parameter, were most of the data at or below the limit of detection? [See Table 3.2 and Database]

Exclude parameter from further analysis

ANALYTICAL EVALUATION (2)
For each parameter, were the differences less than the normal level of reproducibility?

Exclude parameter from further analysis

OPERATION EVALUATION
For each parameter, are the differences between means likely to make an operation difference in the conversion plant?

Exclude parameter from further analysis

EVALUATION OF CORRELATIONS BETWEEN FEEDSTOCK CHARACTERISTICS AND SOILS
Is the regression coefficient >0.7?
Does the plot show a sensible trend?

PRESENTATION OF MEANS
Tabulate means.

PRESENTATION OF RELATIONSHIPS
Plot out the relationship

Do not present graphs.

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?

Exclude parameter from further analysis

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

Exclude parameter from further analysis

EVALUATION OF CORRELATIONS BETWEEN FEEDSTOCK CHARACTERISTICS AND PROVENANCE
Is the regression coefficient >0.7?
Does the plot show a sensible trend?

PRESENTATION OF MEANS
Tabulate means.

PRESENTATION OF RELATIONSHIPS
Plot out the relationship

Do not present graphs.

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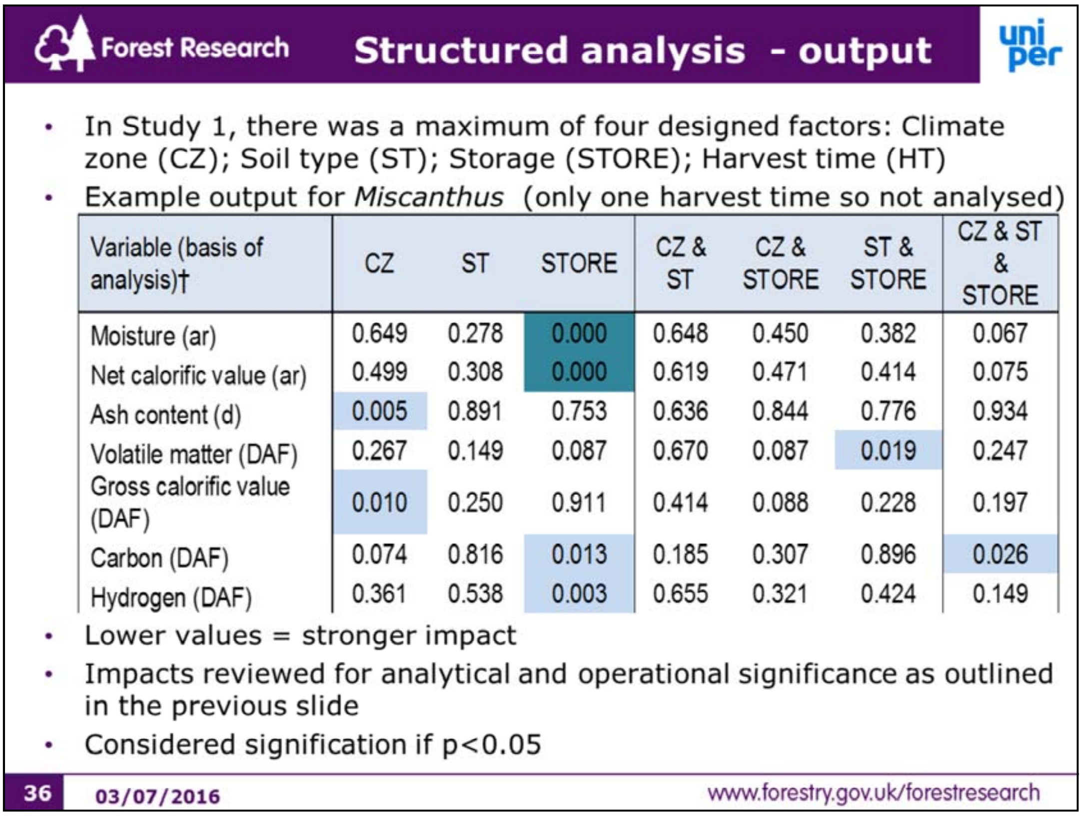
The figures above describe the steps used in Study 1 to extract the critical points for the feedstock characteristics on the left and provenance information on the right. A similar approach was used in Study 2 and 3.



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Structured analysis - output

- In Study 1, there was a maximum of four designed factors: Climate zone (CZ); Soil type (ST); Storage (STORE); Harvest time (HT)
- Example output for *Miscanthus* (only one harvest time so not analysed)

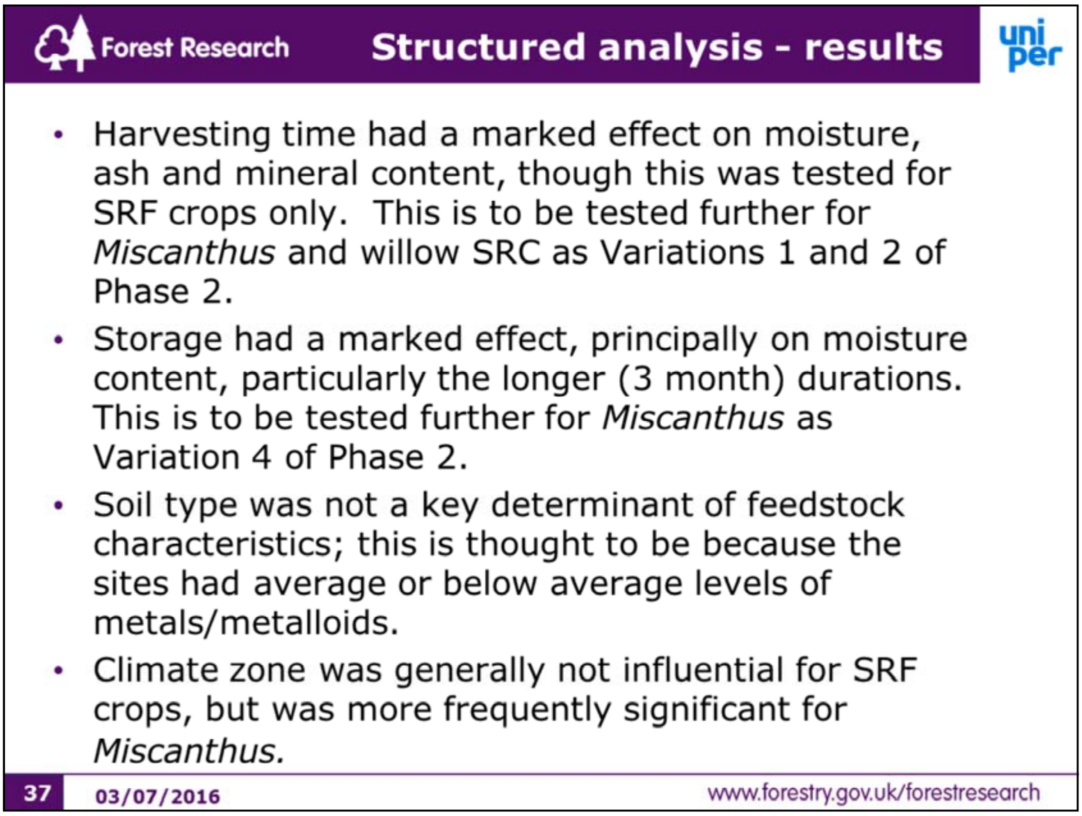
Variable (basis of analysis)†	CZ	ST	STORE	CZ & ST	CZ & STORE	ST & STORE	CZ & ST & STORE
Moisture (ar)	0.649	0.278	0.000	0.648	0.450	0.382	0.067
Net calorific value (ar)	0.499	0.308	0.000	0.619	0.471	0.414	0.075
Ash content (d)	0.005	0.891	0.753	0.636	0.844	0.776	0.934
Volatile matter (DAF)	0.267	0.149	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

- Lower values = stronger impact
- Impacts reviewed for analytical and operational significance as outlined in the previous slide
- Considered signification if $p<0.05$

The four designed factors were:

- Climate Zone (CZ)
- Soil Type (ST)
- Storage (STORE)
- Harvest time (HT)

In the example above, only Climate Zone, Soil Type, and Storage were included.



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Structured analysis - results

- Harvesting time had a marked effect on moisture, ash and mineral content, though this was tested for SRF crops only. This is to be tested further for *Miscanthus* and willow SRC as Variations 1 and 2 of Phase 2.
- Storage had a marked effect, principally on moisture content, particularly the longer (3 month) durations. This is to be tested further for *Miscanthus* as Variation 4 of Phase 2.
- 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 frequently significant for *Miscanthus.*

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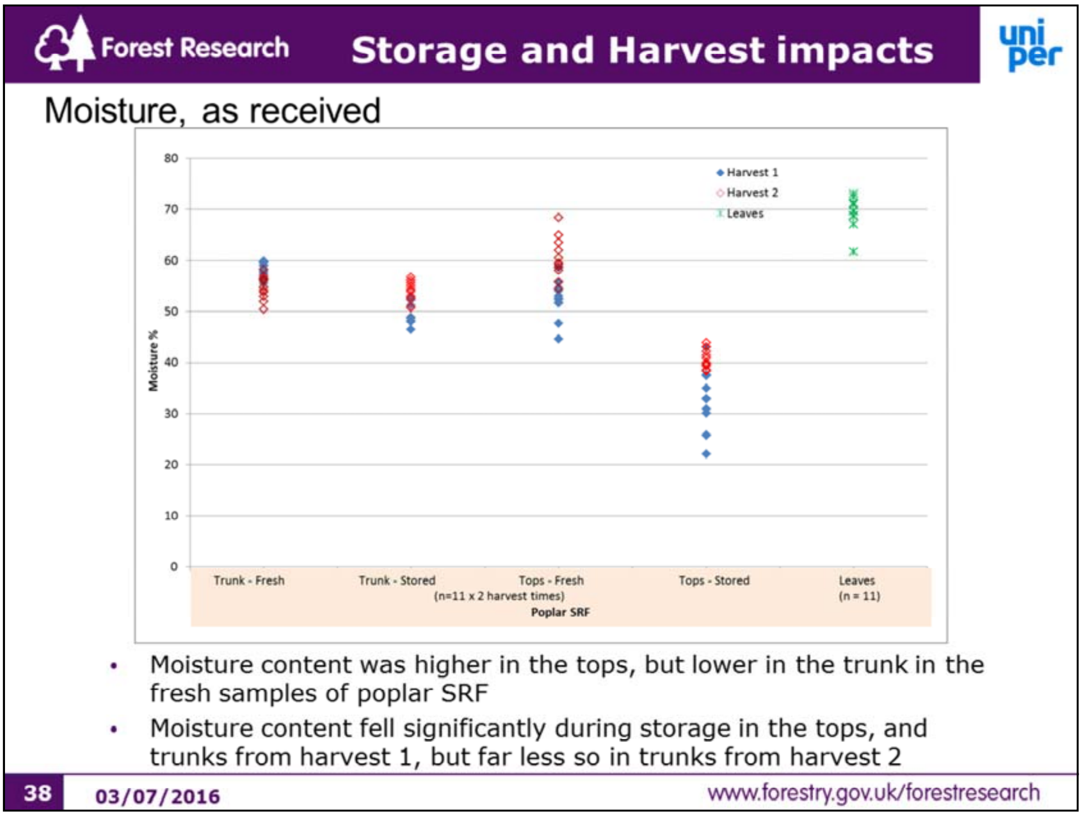
Structured analyses were undertaken using four factors (climate zone, generic soil type, harvest time and storage) and combinations thereof. The effects are summarised here and illustrated in more detail in slides 21 – 27 and 38.

Contrary to our expectations, soil type was not a key determinant of feedstock characteristics. Initially this was thought to be because the statistical analysis used the *predicted* soil type at the site but the analysis was rerun using the actual *measured* soil type at each site and even so soil type had very few significant effects on feedstock characteristics. This is thought to be because the sites had average or below average levels of metals/metalloids.

In contrast harvesting time had a marked effect. Harvesting time was tested for SRF crops only under the initial contract but is being investigated for *Miscanthus* and willow SRC in the contract amendment.

Storage had a marked effect on some characteristics. The impact of storage methods on *Miscanthus* is being investigated in the contract amendment.

Climate zone was generally not influential for SRF crops, but was more frequently significant for *Miscanthus.*



Storage and Harvest impacts

Moisture, as received

- Moisture content was higher in the tops, but lower in the trunk in the fresh samples of poplar SRF
- Moisture content fell significantly during storage in the tops, and trunks from harvest 1, but far less so in trunks from harvest 2

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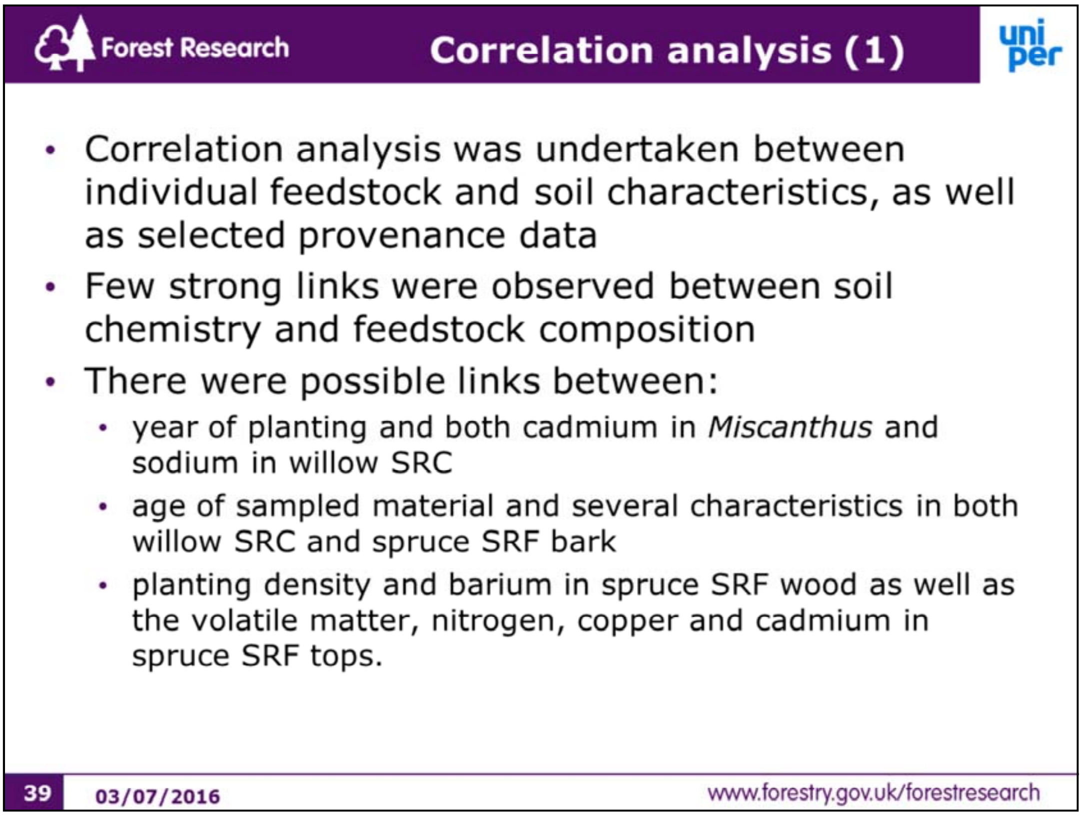
Although moisture content on biomass feedstocks is the single biggest determinant of net calorific value (NCV), and it is therefore of interest to characterize the typical range of the various feedstocks at time of harvest. It is also the one most easily modified by post-harvest treatment (drying). However, while the moisture content immediately post-harvest may vary, the speed of drying during storage also varies between feedstocks and between different plant parts.

Moisture content was significantly higher in samples of tops from the second (late summer) harvest of poplar SRF, at a time when there would have been significant additional leaf content, though the trunk samples from the second harvest appeared slightly lower. After three months' storage the moisture content in most samples had fallen significantly, especially in the tops, with the exception of the trunk samples from the second harvest.



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Correlation analysis (1)

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- Correlation analysis was undertaken between individual feedstock and soil characteristics, as well as selected provenance data
- Few strong links were observed between soil chemistry and feedstock composition
- There were possible links between:
  - year of planting and both cadmium in *Miscanthus* and sodium in willow SRC
  - age of sampled material and several characteristics in both willow SRC and spruce SRF bark
  - planting density and barium in spruce SRF wood as well as the volatile matter, nitrogen, copper and cadmium in spruce SRF tops.

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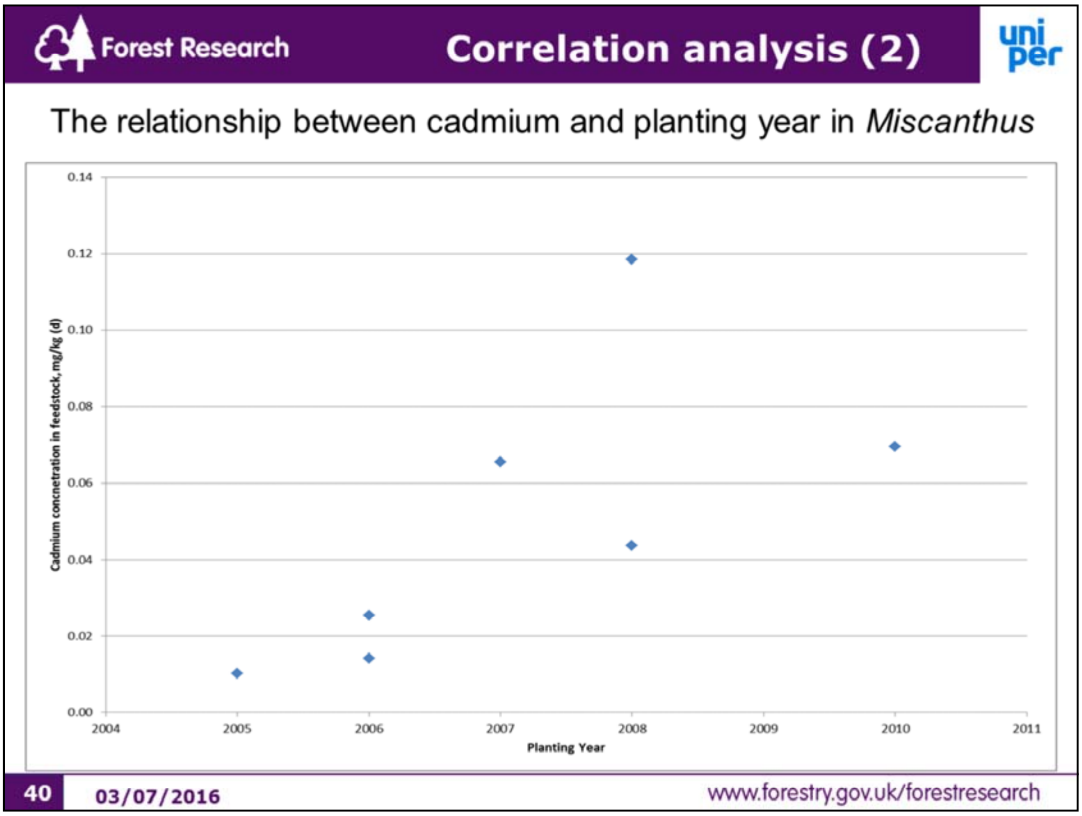
Provenance information subjected to statistical analysis

- Planting density (SRF)
- Soil properties
- Soil classification
- Age of planting
- pH
- elements analysed
- CEC

Provenance information excluded from statistical analysis

- Fertiliser
- Sewage sludge treatment (but note request above)
- Pesticides
- Ground preparation
- Available water
- Lime requirements



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Correlation analysis (2)

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The relationship between cadmium and planting year in *Miscanthus*

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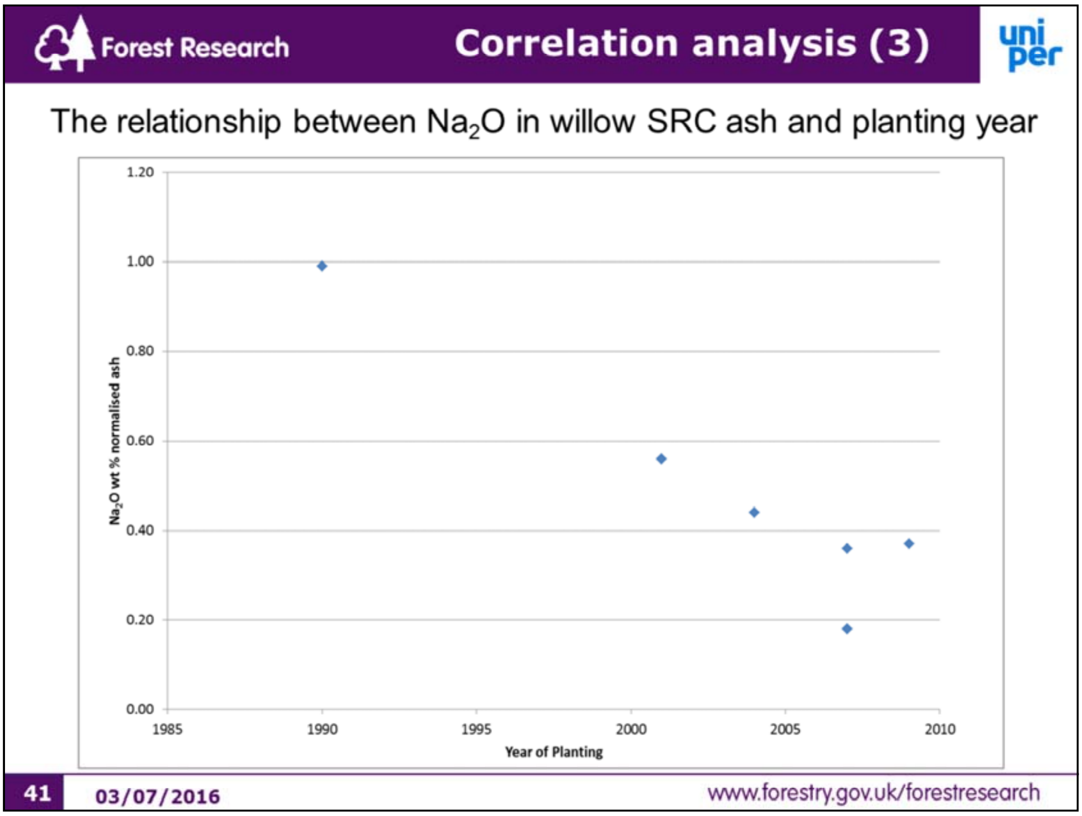
Miscanthus

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). 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.



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Correlation analysis (3)

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The relationship between Na_2O in willow SRC ash and planting year

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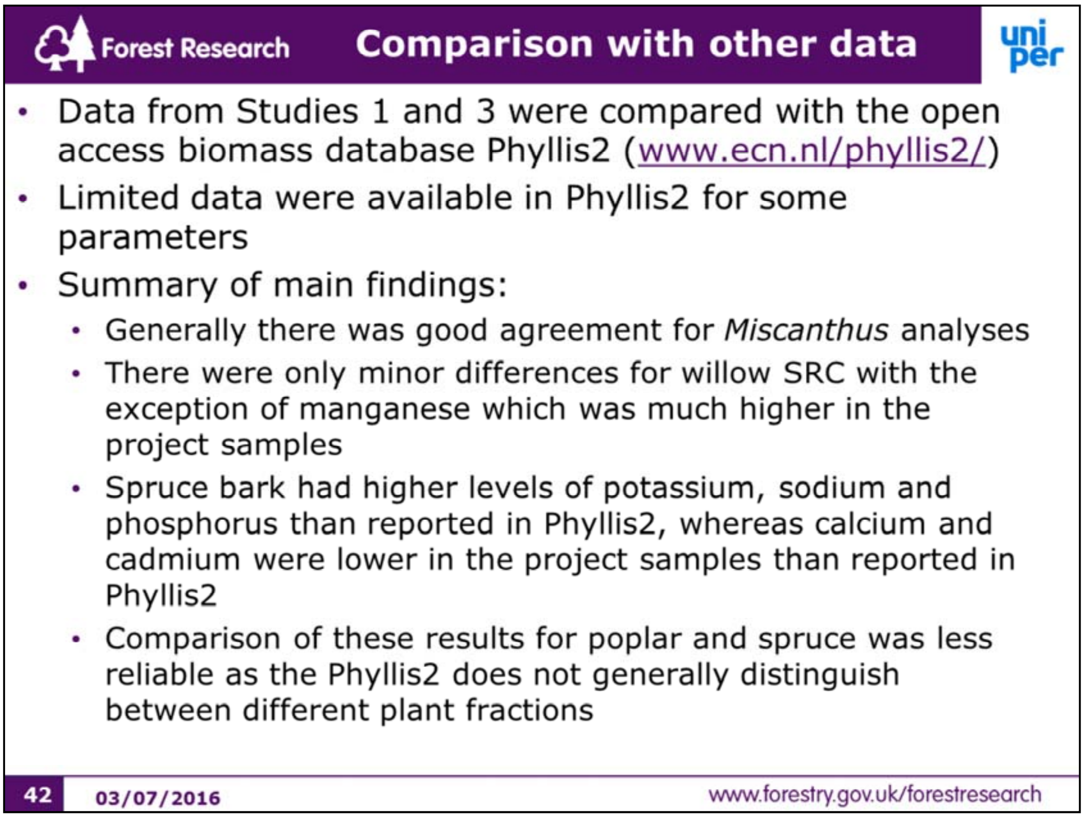
Willow SRC

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, i.e. the more recently planted willow crops had lower concentrations of sodium in the dry fuel and Na_2O in the ash.



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Comparison with other data

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- Data from Studies 1 and 3 were compared with the open access biomass database Phyllis2 (www.ecn.nl/phyllis2/)
- Limited data were available in Phyllis2 for some parameters
- Summary of main findings:
  - Generally there was good agreement for *Miscanthus* analyses
  - There were only minor differences for willow SRC with the exception of manganese which was much higher in the project samples
  - Spruce bark had higher levels of potassium, sodium and phosphorus than reported in Phyllis2, whereas calcium and cadmium were lower in the project samples than reported in Phyllis2
  - Comparison of these results for poplar and spruce was less reliable as the Phyllis2 does not generally distinguish between different plant fractions

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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.

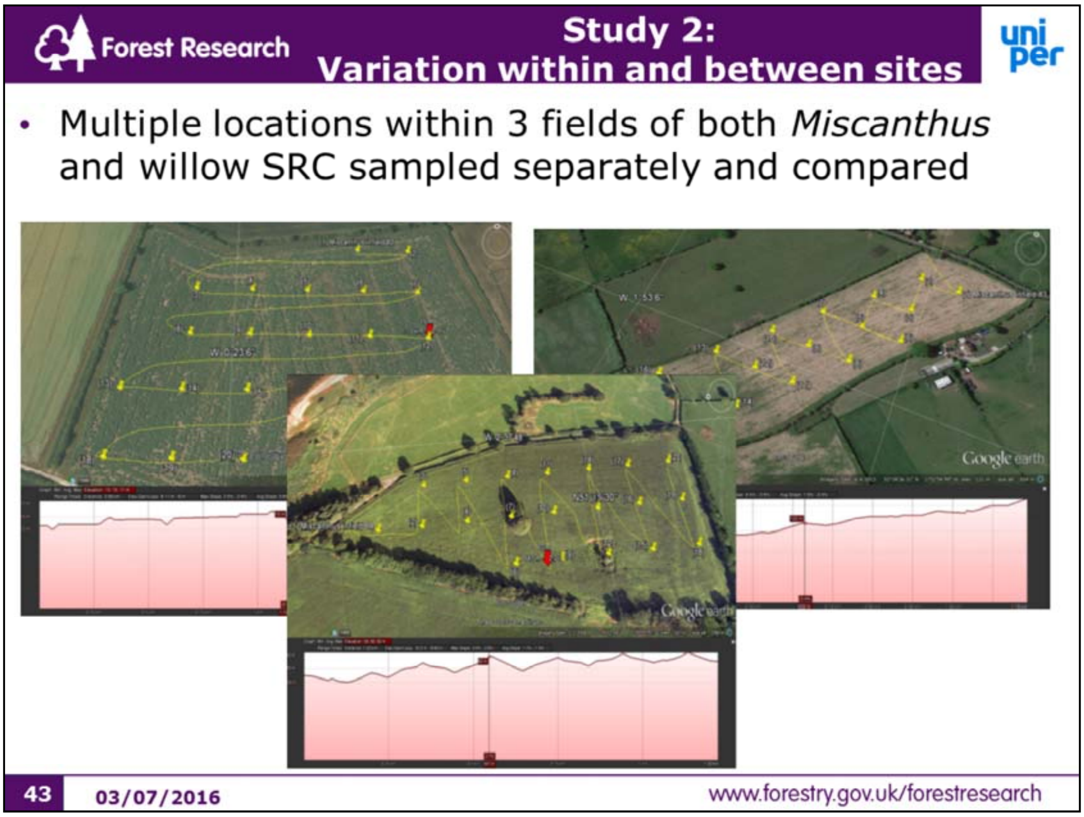
A comparison of the feedstock characteristics collected within the project with this database indicated generally good agreement for *Miscanthus* and only minor differences for willow SRC with the exception of manganese which was much higher in the project samples.

Comparison of the data for poplar and spruce was less reliable as the Phyllis2 does not generally distinguish between different plant fractions.

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.

This confirms that the results of the project are reliable therefore:

- Modelling and further analysis, such as within the TEAB project, are based on credible information
- the few occasions where there were departures from the norm may be worth further investigation


Forest Research

Study 2: Variation within and between sites

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- Multiple locations within 3 fields of both *Miscanthus* and willow SRC sampled separately and compared

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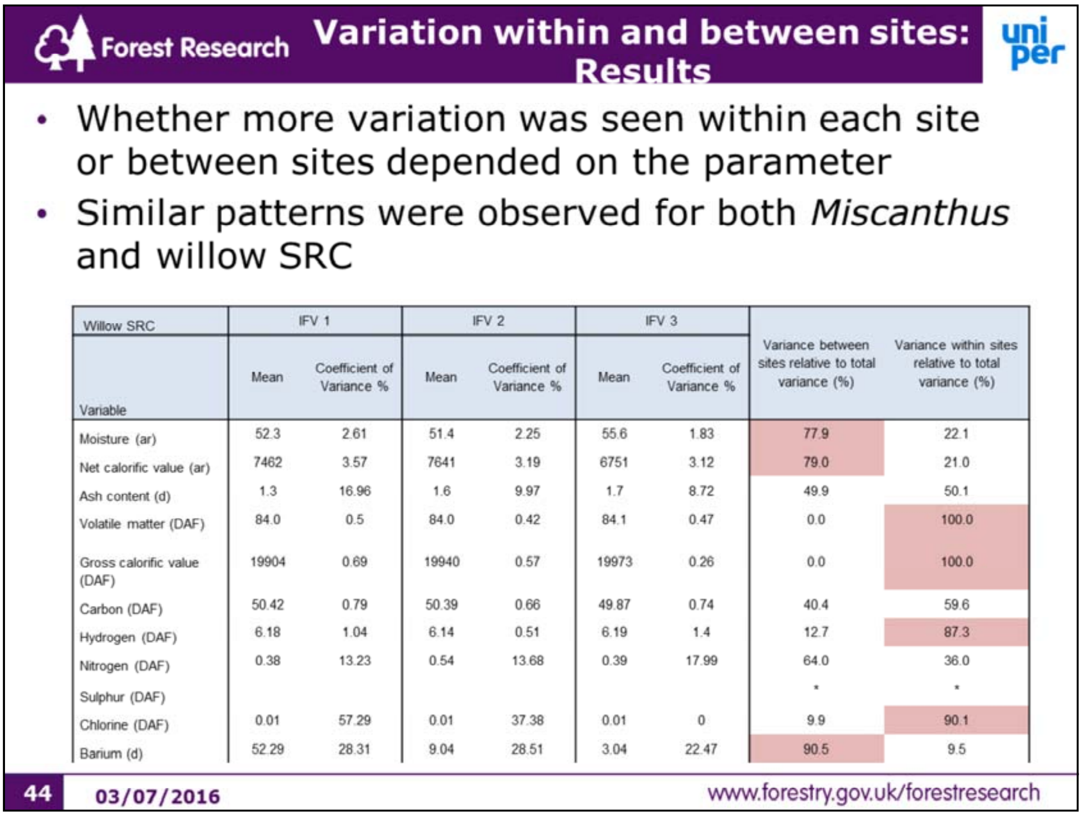
Study 2 investigated feedstock variability within a site (*Miscanthus* and one variety of willow SRC only) addressing Hypothesis 8. Whilst Study 1 provided an overall average for each site and should be typical of the harvested crop, there could be situations where only parts of site are harvested at any one time. There is therefore a practical value in understanding the differences found across individual sites.

In order to assess how much of the variation we saw between samples from different sites might also be observable in samples taken from individual sites, with nominally the same site properties and management, the project selected three sites for each of *Miscanthus* and willow SRC.

At each of the three in-field variation sites, 20 biomass samples were collected and analysed separately which allowed the variability within each field and between fields to be investigated. Site maps indicating the location and elevation of each sampling location within the field are shown above; 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.



Variation within and between sites: Results

- Whether more variation was seen within each site or between sites depended on the parameter
- Similar patterns were observed for both *Miscanthus* and willow SRC

Willow SRC	IFV 1		IFV 2		IFV 3			
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)	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

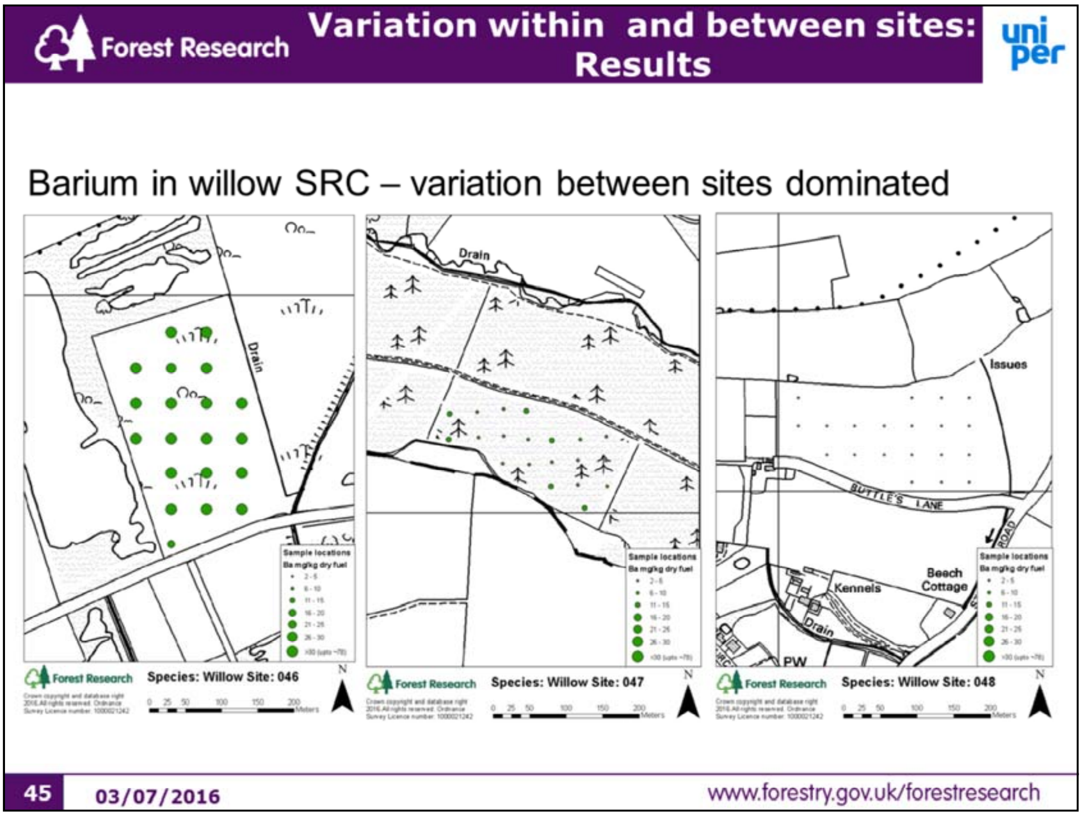
The table is an example of the coefficient of variation for a sample of parameters in each of three willow SRC sites (IFV1, IFV2, and IFV3) and at the right the variance between sites relative to the total variance and the variance within sites relative to the total variance. If similar levels of variance were observed between and within sites both far right columns are left uncoloured; if there was appreciably more (>66%) variation either between or within sites, a pink cell fill was added to the column with the greater variance.

Miscanthus

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.

Willow SRC

For some feedstock characteristics there was greater variation from site to site than within-field, for example moisture, NCV 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.



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Variation within and between sites: Results

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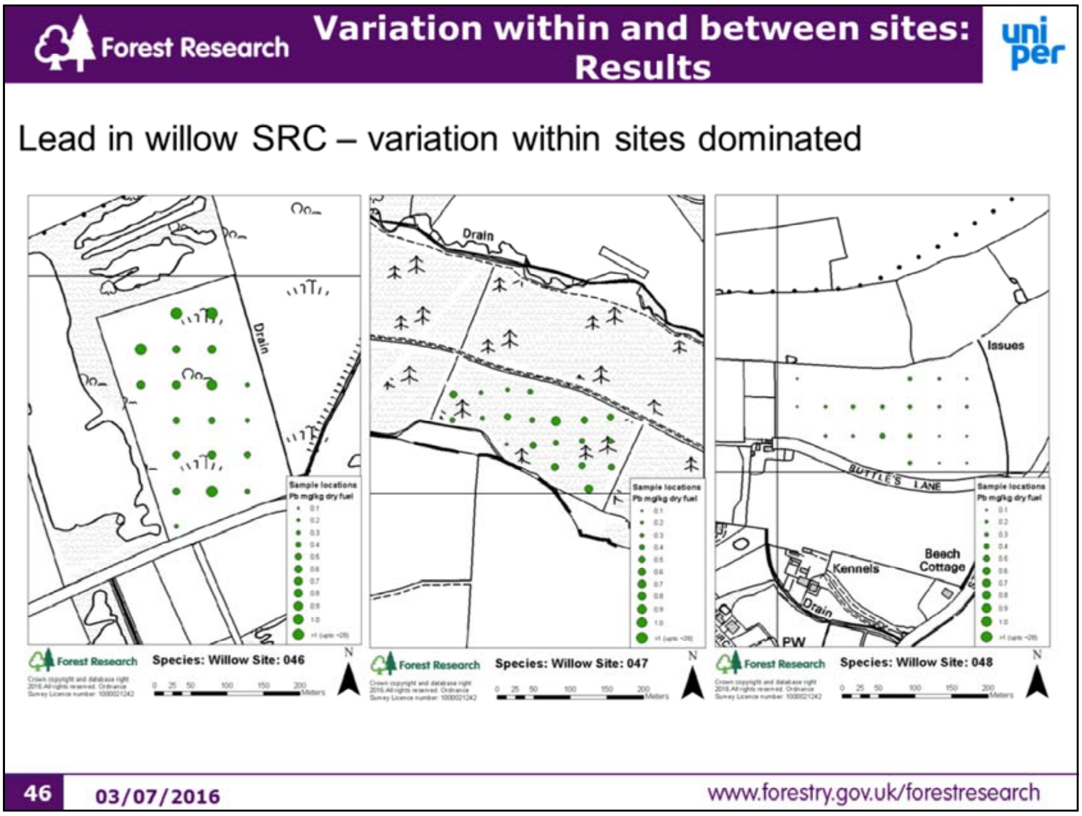
Barium in willow SRC – variation between sites dominated

In terms of trace and macro elements, again the behaviour of barium was striking in both *Miscanthus* and willow SRC (here we see willow SRC) with the willow SRC samples from in-field variation site 1 showing very high concentrations compared to the other sites. Unfortunately no soil samples were analysed for barium, so the cause of this behaviour could not be traced.



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Variation within and between sites: Results

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Lead in willow SRC – variation within sites dominated

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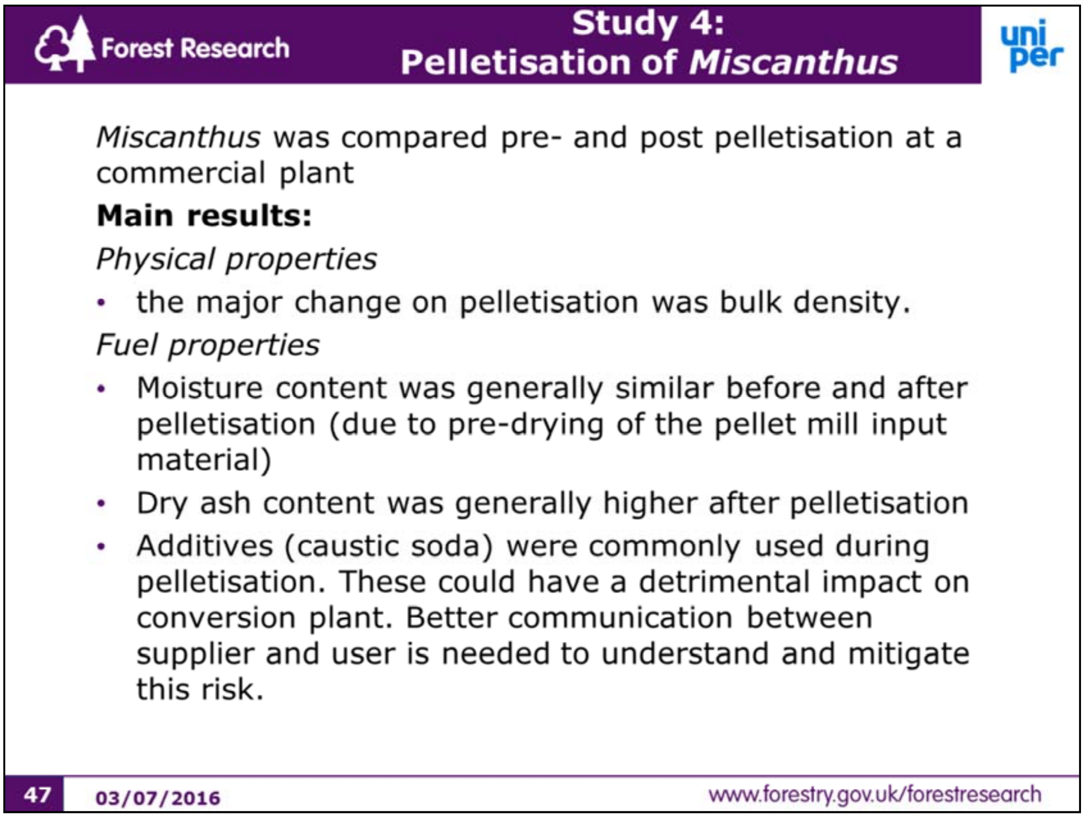
In both feedstocks the variation in lead was very much greater within sites than between sites.



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Study 4: Pelletisation of *Miscanthus*

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Miscanthus was compared pre- and post pelletisation at a commercial plant

Main results:

Physical properties

- the major change on pelletisation was bulk density.

Fuel properties

- Moisture content was generally similar before and after pelletisation (due to pre-drying of the pellet mill input material)
- Dry ash content was generally higher after pelletisation
- Additives (caustic soda) were commonly used during pelletisation. These could have a detrimental impact on conversion plant. Better communication between supplier and user is needed to understand and mitigate this risk.

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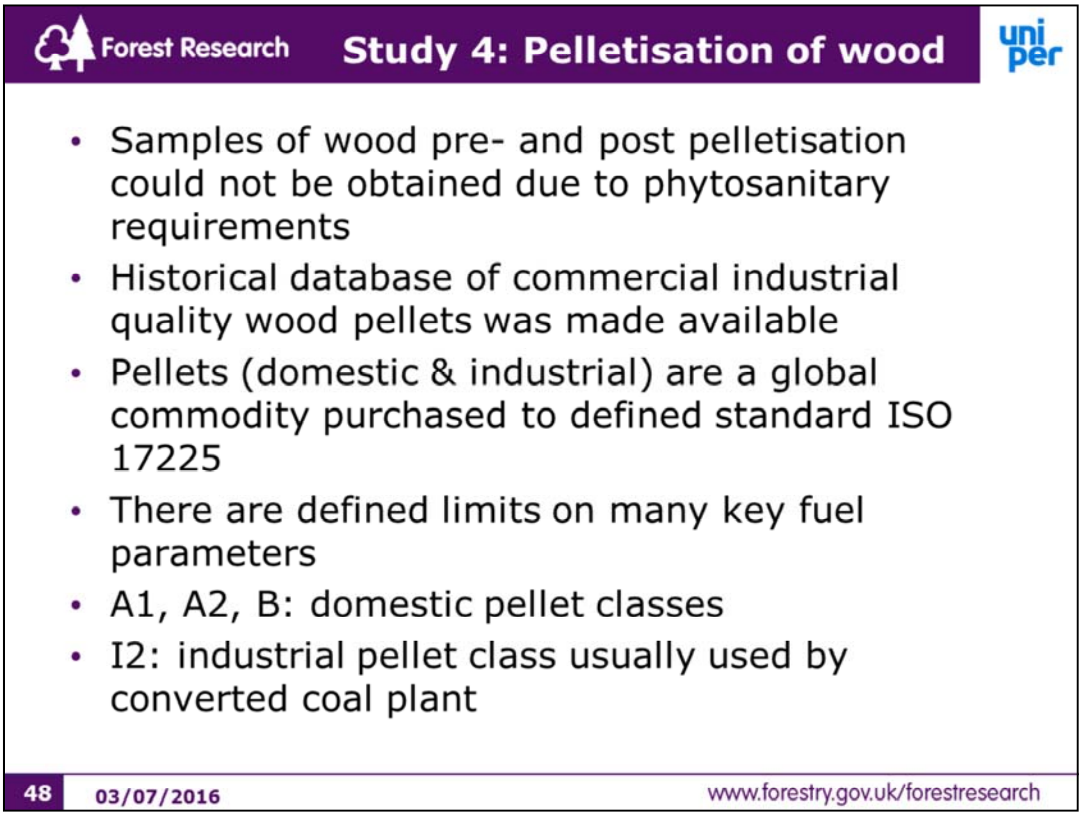
The use of biomass in both large scale power generation and small scale heat is often in the form of pellets. These provide a clean, consistent product that flows easily, and is also considerably densified for convenience of transport and storage.

Study 4 investigated pellet properties. The process of pelletising may alter the composition compared to the raw feedstock, which was formalised as hypothesis 9. 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 biomass sampled within the project.

Study 4 set out to evaluate the extent of this and any other changes in *Miscanthus* properties as a result of pelletisation. This exercise has clearly demonstrated the dramatic change in physical properties of biomass following pelletisation, but has yielded less information on the chemical characteristics. The major change on pelletisation was bulk density. The raw *Miscanthus* was provided in dried, chopped form of approx. 50 mm lengths with 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%.

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 issues of contamination by additives described in the slide.

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 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.



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Study 4: Pelletisation of wood

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- Samples of wood pre- and post pelletisation could not be obtained due to phytosanitary requirements
- Historical database of commercial industrial quality wood pellets was made available
- Pellets (domestic & industrial) are a global commodity purchased to defined standard ISO 17225
- There are defined limits on many key fuel parameters
- A1, A2, B: domestic pellet classes
- I2: industrial pellet class usually used by converted coal plant

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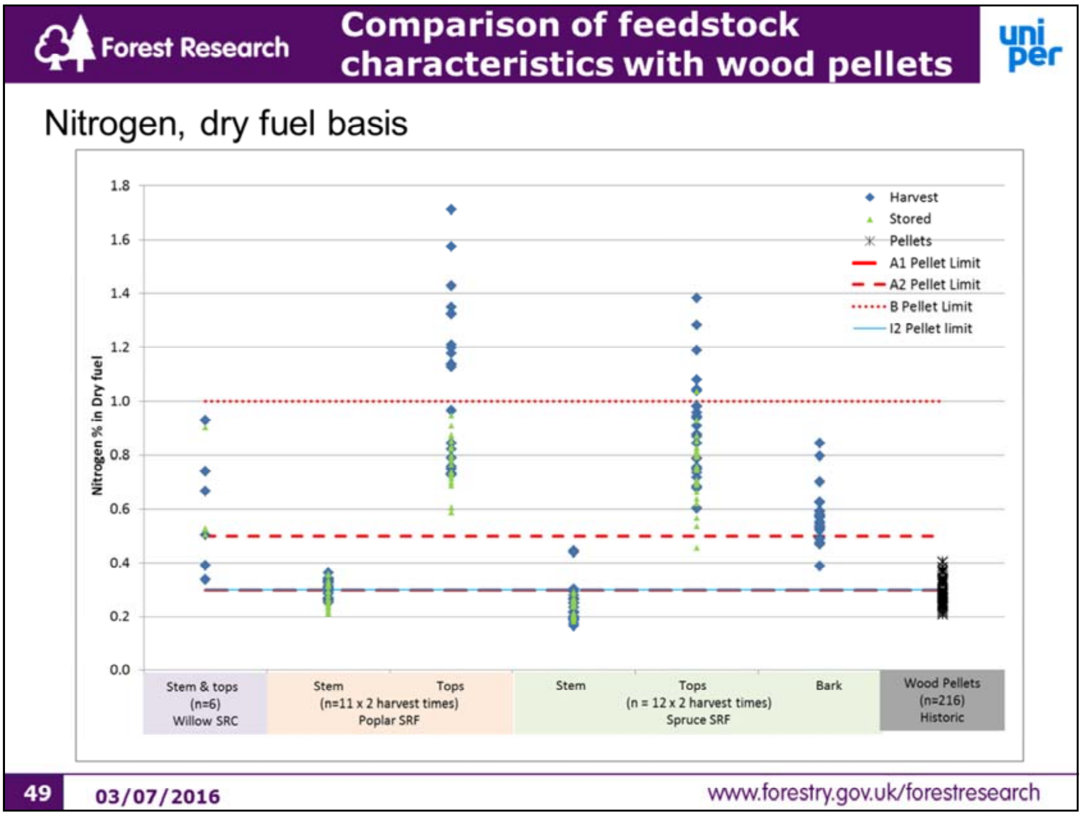
As well as investigating the effect of pelletising *Miscanthus*, Study 4 drew on the extensive database of wood pellet properties from E.On to identify the mean physical and chemical properties of commercial wood pellets and compare them with the properties of feedstocks from the Study 1.

Although samples of *Miscanthus* could be compared before and after pelleting, this could not be done directly for the wood pellets as they were all sourced overseas and unfortunately it was not possible to obtain samples of the raw feedstock because of the phytosanitary regulations relating to the import of wood.

The properties of our samples could also be compared with the values required to meet the various industrial or domestic wood pellet standards.



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Comparison of feedstock characteristics with wood pellets

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Nitrogen, dry fuel basis

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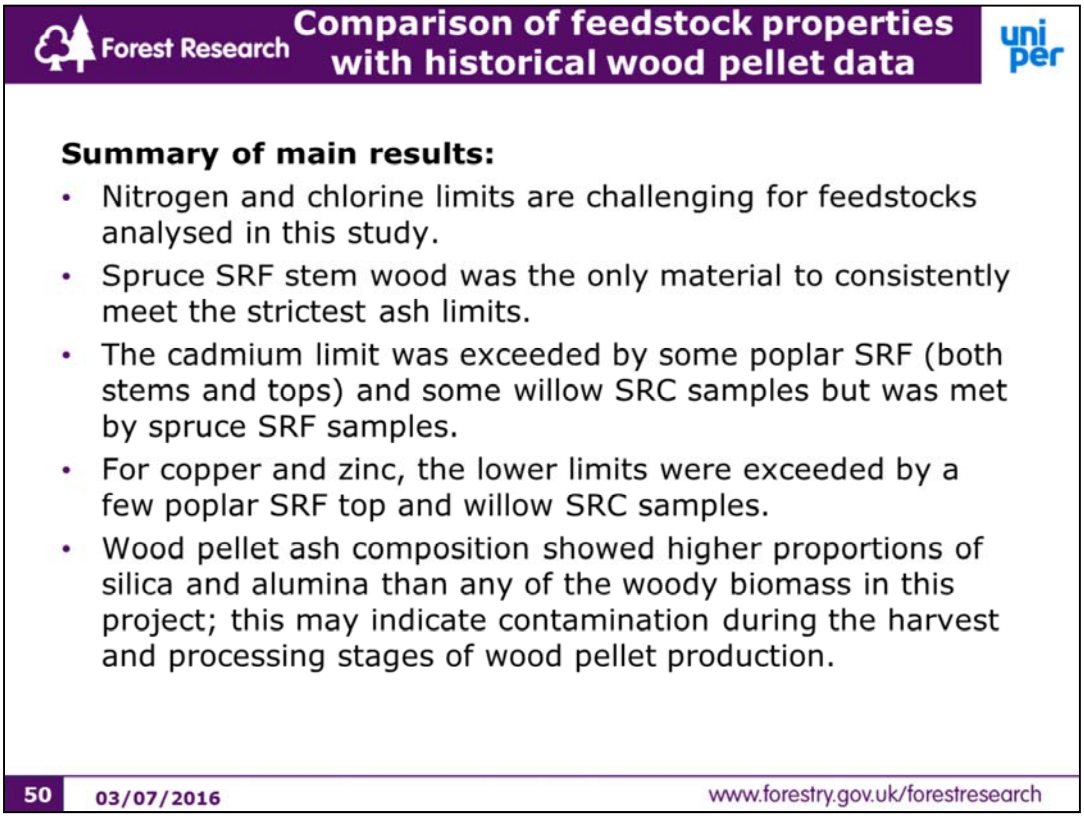
ISO 17225-2 quotes three different dry nitrogen limits for commercial and domestic pellet classifications A1, A2 and B; it is interesting to note that these are all equivalent to, or higher than that for the Industrial grade pellet I2. In terms of the ETI samples, only the spruce SRF stem wood consistently meets the strictest criteria (A1 and I2 pellet - <0.3% nitrogen (dry)), with the tops and bark exceeding it by some margin. 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.



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Comparison of feedstock properties with historical wood pellet data

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Summary of main results:

- Nitrogen and chlorine limits are challenging for feedstocks analysed in this study.
- Spruce SRF stem wood was the only material to consistently meet the strictest ash limits.
- The cadmium limit was exceeded by some poplar SRF (both stems and tops) and some willow SRC samples but was met by spruce SRF samples.
- For copper and zinc, the lower limits were exceeded by a few poplar SRF top and willow SRC samples.
- Wood pellet ash composition showed higher proportions of silica and alumina than any of the woody biomass in this project; this may indicate contamination during the harvest and processing stages of wood pellet production.

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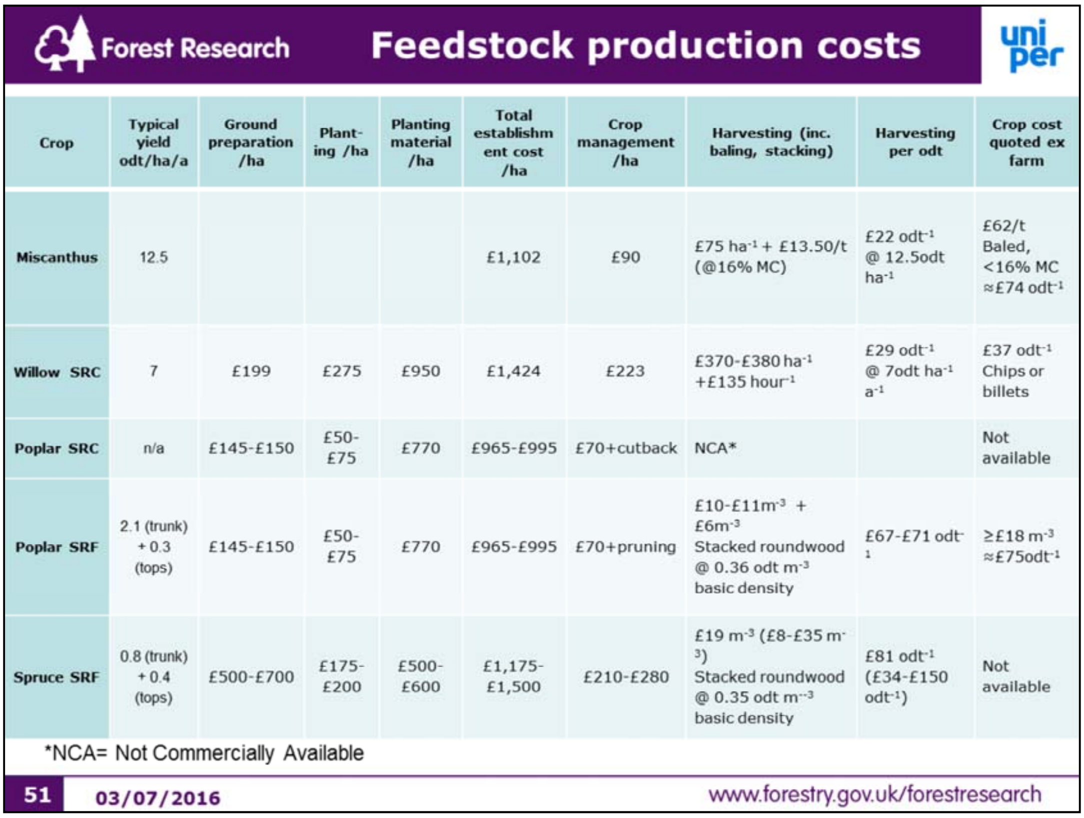
Data provided on internationally traded wood pellets by Uniper (formerly known as E.On) highlighted an extremely consistent and homogeneous fuel and were tightly clustered compared to the raw feedstocks analysed in this project.

A number of quality standards exist for wood pellets depending on the market application and these have recently been defined in ISO17225-2:2014.

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 noticeable 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 (debarked) spruce SRF stem 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 (non-industrial) pellet types A1, A2 and B and this is exceeded by a proportion of the poplar SRF dataset (both stem 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.



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Feedstock production costs

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Crop	Typical yield odt/ha/a	Ground preparation /ha	Plant-ing /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*		Not available
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})	Not available

*NCA= Not Commercially Available

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The cost figures 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.**

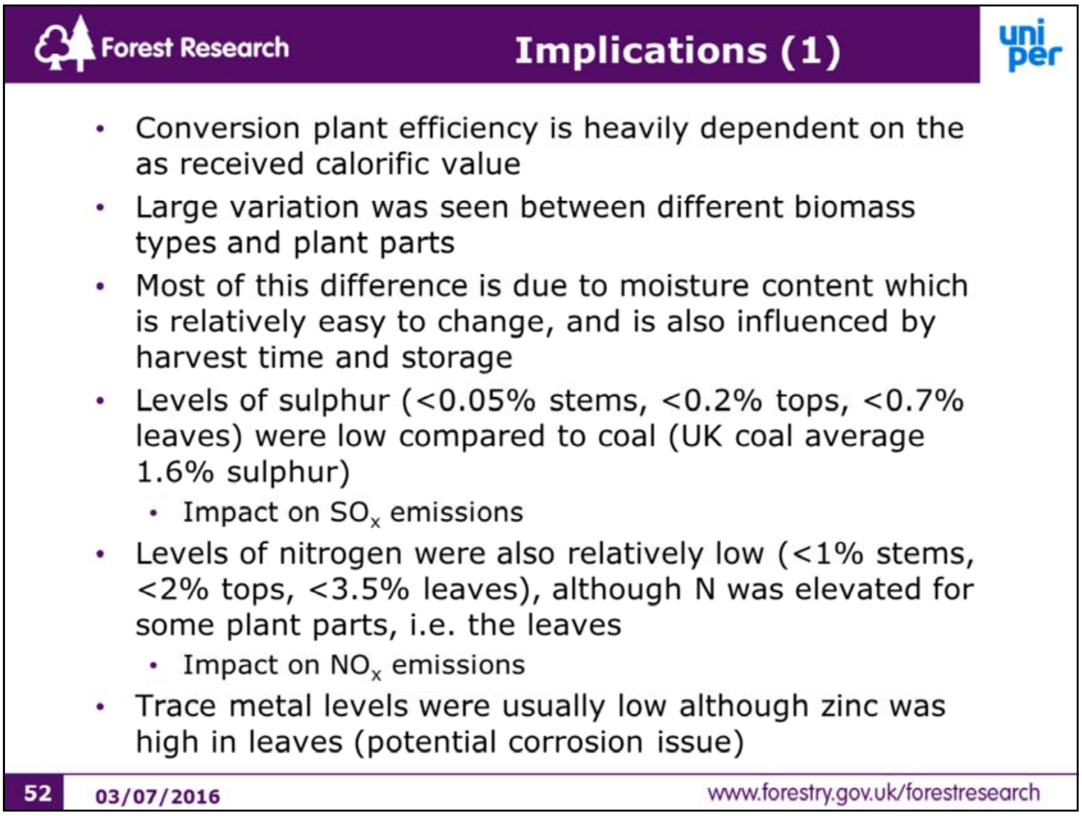
In general terms, the main differences between the feedstock types were in the initial establishment and management costs.

Spruce SRF and poplar SRF incurring higher costs in the early years 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.

Willow SRC costs were typically higher than *Miscanthus*, largely due to the additional cut back operations at the end of year one

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.

N.B. Spruce SRF costs were estimated because spruce is not currently managed as Short Rotation Forest (SRF) in the UK. Consequently, the cost of commercial harvesting at around 15 years is not clear.



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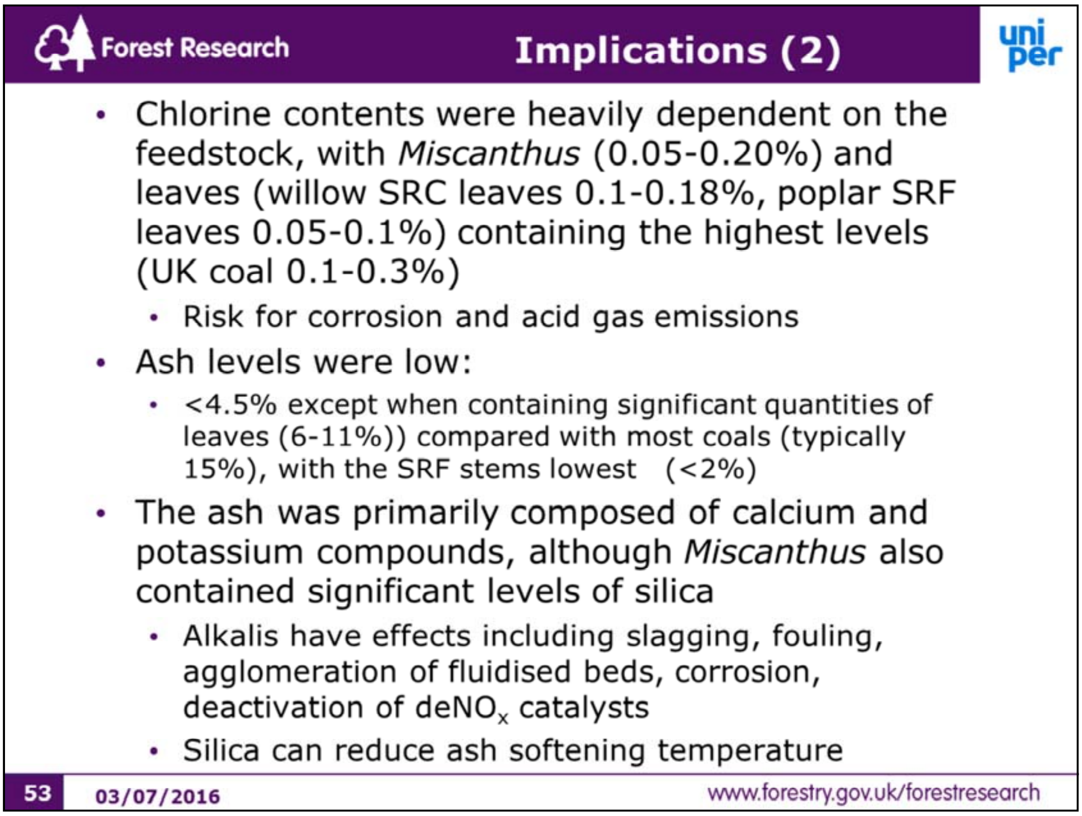
Implications (1)

- Conversion plant efficiency is heavily dependent on the as received calorific value
- Large variation was seen between different biomass types and plant parts
- Most of this difference is due to moisture content which is relatively easy to change, and is also influenced by harvest time and storage
- Levels of sulphur (<0.05% stems, <0.2% tops, <0.7% leaves) were low compared to coal (UK coal average 1.6% sulphur)
  - Impact on SO_x emissions
- Levels of nitrogen were also relatively low (<1% stems, <2% tops, <3.5% leaves), although N was elevated for some plant parts, i.e. the leaves
  - Impact on NO_x emissions
- Trace metal levels were usually low although zinc was high in leaves (potential corrosion issue)

This project produced some results that were as expected, and some that were something of a surprise. It was, however, possible to draw some valuable conclusions from the study, with implications for how best to make use of UK energy crops, the differences between different feedstocks, and between biomass and coal.

Some general implications of the results of this study are set out in this slide, with more specific implications outlined in slides 53 and 54.



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Implications (2)

- Chlorine contents were heavily dependent on the feedstock, with *Miscanthus* (0.05-0.20%) and leaves (willow SRC leaves 0.1-0.18%, poplar SRF leaves 0.05-0.1%) containing the highest levels (UK coal 0.1-0.3%)
  - Risk for corrosion and acid gas emissions
- Ash levels were low:
  - <4.5% except when containing significant quantities of leaves (6-11%)) compared with most coals (typically 15%), with the SRF stems lowest (<2%)
- The ash was primarily composed of calcium and potassium compounds, although *Miscanthus* also contained significant levels of silica
  - Alkalis have effects including slagging, fouling, agglomeration of fluidised beds, corrosion, deactivation of deNO$_x$ catalysts
  - Silica can reduce ash softening temperature

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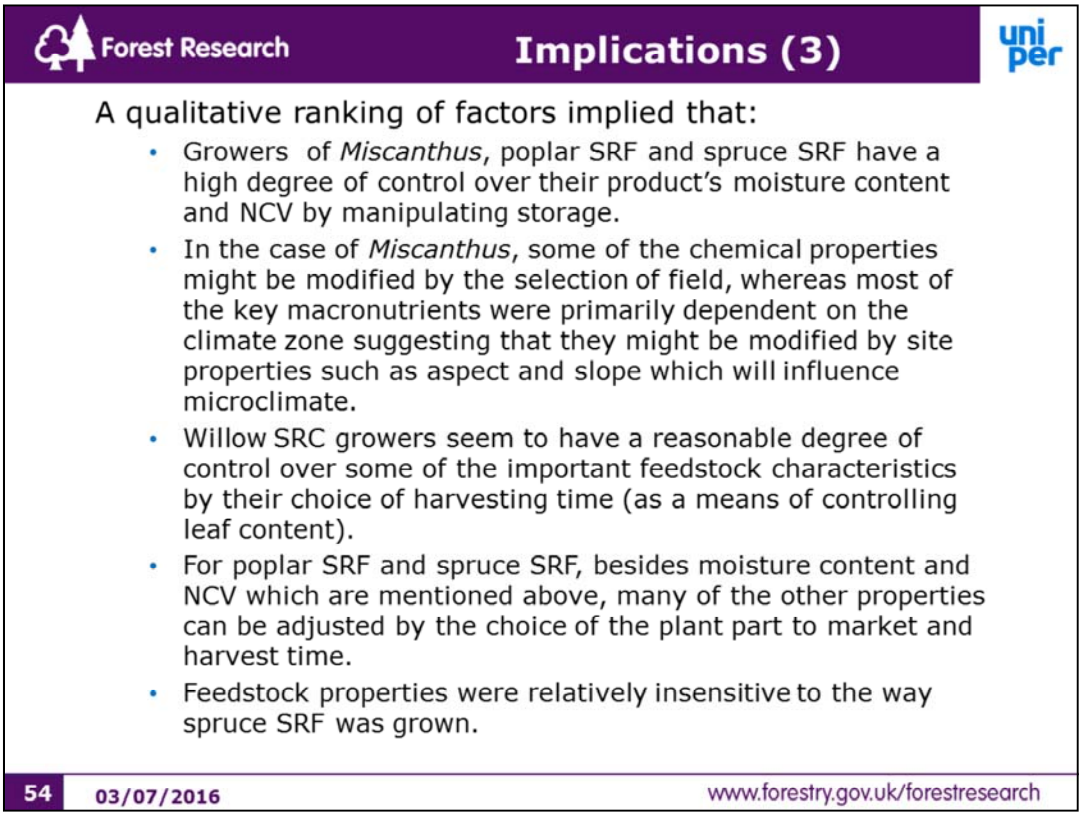
Some more specific implications concerning the choice of feedstock and factors such as corrosion, slagging and fouling in combustion equipment are presented in this slide.

In general ash and chlorine levels were significantly lower than UK coal.



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Implications (3)

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A qualitative ranking of factors implied that:

- Growers of *Miscanthus*, poplar SRF and spruce SRF have a high degree of control over their product's moisture content and NCV by manipulating storage.
- In the case of *Miscanthus*, some of the chemical properties might be modified by the selection of field, whereas most of the key macronutrients were primarily dependent on the climate zone suggesting that they might be modified by site properties such as aspect and slope which will influence microclimate.
- 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.

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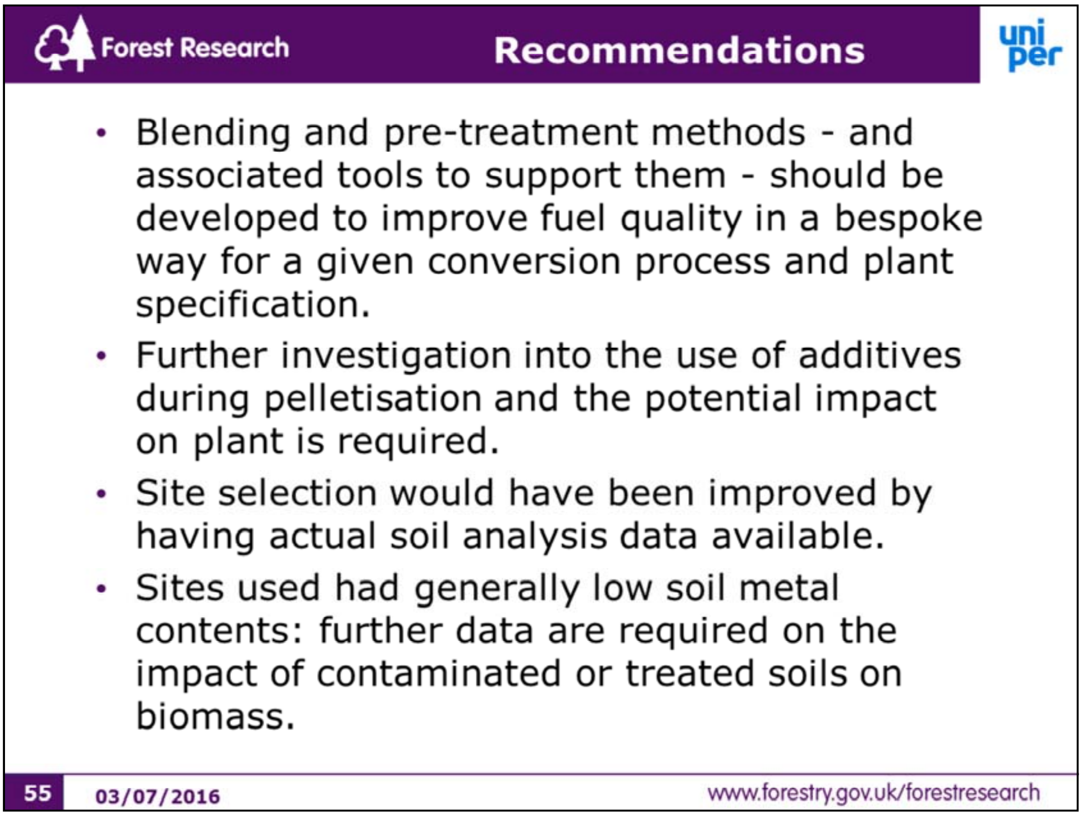
A qualitative ranking was used to evaluate all the site factors and provenance information shown to influence the feedstock properties in a significant way, in terms of their statistical and analytical significance as well as their operational effect. There was no simple ranking common to all feedstocks and plant parts – feedstock characteristics were not affected in a consistent way by site factors or crop management.

The implications for growers are summarised above. In addition, the qualitative ranking suggested that for all feedstocks, buyers should give consideration to the feedstock characteristics of prime importance in a particular application.



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Recommendations

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- Blending and pre-treatment methods - and associated tools to support them - should be developed to improve fuel quality in a bespoke way for a given conversion process and plant specification.
- Further investigation into the use of additives during pelletisation and the potential impact on plant is required.
- Site selection would have been improved by having actual soil analysis data available.
- Sites used had generally low soil metal contents: further data are required on the impact of contaminated or treated soils on biomass.

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It was possible to draw a number of recommendations, both concerning the study and how UK feedstocks can best be exploited, based on the results of our analysis. These are set out in this slide.