IDENTIFICATION AND CHARACTERISATION OF FACTORS AFFECTING LOSSES IN THE LARGE-SCALE, NON-VENTILATED BULK STORAGE OF WOOD CHIPS AND DEVELOPMENT OF BEST STORAGE PRACTICES

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Executive Summary

Objectives

To determine and characterise factors affecting losses in the large-scale non-ventilated bulk storage of wood chips and to develop best storage practices which can be implemented on a commercial scale.

Introduction

Literature regarding the commercial storage of wood chip is limited. Research has been conducted for other wood handling industries eg wood pulp and paper production, but in many cases this work is irrelevant to the large scale storage of wood chip for the biomass industry. ARBRE Energy Limited has built the UK's first biomass power generation plant in North Yorkshire. The fuel used is a mixture of forestry residue (derived from woodland management practices eg thinning) and energy crops such as willow Short Rotation Coppice (SRC). SRC is harvested during the winter months on a three yearly rotation and is often not immediately required at the power station. Therefore, the wood chip must be stored on the farmer's land or at a storage site close to the plant for an indefinite period of time. Similarly, the forestry material will be stockpiled at the edge of the forest until it is required at the station. However, it is hoped that this delay will allow the natural air-drying of the wood. The fuel entering the plant must be below a moisture content of 30 percent in order to maintain generation efficiencies. Another important fuel specification is the particle size; the ideal wood chip is greater than 3mm and less than 30mm. Wood chip degradation (dry matter losses) must be minimised if the energy crop/fuel is to remain economically viable.

Previously ARBRE has constructed large piles of forestry material with a trapezoid cross-section. The chips were compacted on delivery using heavy machinery. The purpose of compaction was to reduce air flow and minimise aerobic degradation processes, although this approach was not without its problems. In older piles the temperatures rose and fires started, highlighting the necessity to establish best storage practices.

Work conducted

Two wood chip piles were established at a storage site near Great Heck in North Yorkshire. One pile was constructed with willow chip and the second was constructed with wood chips from broad leaf forestry residues. Thermocouples were buried within the piles to measure temperature changes during storage. Samples were taken periodically from various depths within the piles to investigate chemical changes. Spore measurements were made to asses the health risk of exposure to partly degraded wood chips. A computer model was constructed to try to understand heat and air flows within the piles.

Results

Weather information was obtained from a local met station to assess the influence of ambient conditions on the piles.

Moisture content measurements revealed that the top layers in each pile (0.1m and 0.5m deep in the SRC and forestry residue piles respectively) were predominately wetter than the core layers (1.5-3.0m deep) throughout the duration of the trial. After 50 days in storage the core layers dried, reaching a static moisture content of approximately 30%. The piles' moisture content correlates tentatively with the average monthly rainfall.

The ash content analysis did not show any trends relating the ash content to the chip depth. The ash content of the SRC pile remained constant at approximately 1-2%. The levels in the forestry residue pile fluctuated dramatically, most likely due to random scatter in the measurements.

No clear trends were found when the calorific value of the piles was assessed in relation to the wood chip depth. It was noted that the surface layer of the pile had a lower calorific value than the core layer, a finding that was common to both piles.

Thermocouple temperature measurements were grouped together to identify trends relating to particular areas of the piles. The core and surface layers were analysed together. It was discovered that the SRC pile behaved as one thermal mass throughout the duration of the storage period. The core temperature of the forestry residue pile was higher than the surface temperature throughout the trial. There was no trend between the centreline temperature and the wood chip depth in either the SRC or the forestry residue pile. When the ambient temperature was subtracted from the results it showed that overall both piles reached an excess temperature of around 50°C before it declined to 10°C.

No relationship was found between the number of days in storage and the particle size in either the SRC or the forestry residue piles. The global average amount of fines was 5.0% in the forestry pile and 1.0% in the SRC pile.

The water soluble carbohydrate content (WSC) in the SRC pile was erratic at the start of the trial before declining to a level below 0.5% for the remainder of the trial. It appeared that the liberation and deployment of water-soluble carbohydrate was uniform throughout the pile. In the forestry residue pile two peaks were seen at 75 and 225days into storage. The average content was 1.25%. No differences between content and depth were found.

Latic acid levels showed signs of early fermentation activity, but sample variability indicated the heterogeneity of in stack conditions. The lactic acid content of the SRC pile remained constant at less than 800mg/kg after an initial fluctuation at the start of the trial. The lactic acid content in the forestry residue pile followed a different pattern as two peaks were seen at 15 and 117days into the storage period. The average content was also less than 800mg/kg.

The spore measurements (focusing upon the indicator species, *Thermophilic actinomycetes* and *Aspergillus fumigatus*) revealed that no change in spore levels occurred during the pile disturbance created artificially at the end of the storage period to mimic chip handling operations. Levels recorded (194colony forming units/m^3) were well within the current Health and Safety guidelines.

The bulk density of the wood chip was measured at the start and end of the storage period. The difference between the two was 28.76oven dried kilograms per metre cubed (odkg/m^3) in the SRC pile and 17.89odkg/m^3 in the forestry pile.

It was found that the near infra-red reflectance spectroscopy (NIRS) analyses provided a good correlation between wet chemistry and dry matter, lignin and cellulose content. This technique has the potential to be used for the prediction of wood chip degradation in store and rapid assessment of fuel quality and type on arrival at plant.

Conclusions and recommendations

1. Natural air drying can reduce wood chip moisture content to acceptable levels without unacceptable chip degradation, but only in the core of a pile where the chips are insulated from the effects of the weather by the surface layer above
2. Chips should be piled loose, rather than being compacted, in order to maximise convective heat loss and related moisture loss, and reduce risk of spontaneous combustion.
3. Harvesting and chipping should be optimised to provide a chip with as uniform a chip size as possible and with the minimum of fines in order to give a low resistance to air flow. The chip size should be as large as is possible given the constraints of the handling equipment at the plant.
4. Piles could be built higher than the piles in this study to increase the core : surface ratio. However piles should not be built so high that there is a danger of temperatures reaching levels at which spontaneous combustion may occur. Based on this work, and literature, a 10m pile height would seem reasonable if machinery allows.
5. Alternative pile shapes, which increase the core: surface ratio, should be considered. CFD modelling may give an insight as to whether alternative shapes will still allow adequate air flow.
6. Covering materials that will shed a large proportion of rainfall while still allowing plenty of air movement should be investigated.
7. Careful scheduling of material removal from store can minimise the amount of dry matter loss.
8. No evidence of a significant health risk arising from exposure to wood dust or fungal spores during routine operations was found. However, based on experience in Sweden, precautions should be taken in handling wood chip that has been in store to minimise exposure.

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1 INTRODUCTION

Biomass has been identified as a potential major renewable energy source. There are many possible biomass fuels, but it seems likely that wood chip will be a major one. Biomass power plants will operate 24 hours/day, year round, whereas wood chip production is seasonal. Woody energy crops (eg short rotation coppice, SRC) are harvested during their dormant period. Bad winter weather can limit the period during which forestry residues (FR) can be extracted. This creates a need to store wood chips in order to guarantee a steady supply to power plants.

Wood chip fuel will need to conform to certain specifications in order to be suitable for use in power plants. Specifications will typically include limits on moisture contents, ash content, particle size distribution and calorific value. For many power plants designs, the moisture content must be reduced between harvesting and delivery to the power plant. For example, willow SRC typically has a moisture content of 50-55% wet basis at harvest, but the ARBRE Biomass Integrated Gasification – Combined Cycle (BIG-CC) power plant requires wood chip fuel with a maximum wet basis moisture content (w.b.m.c.) of 30%. Whatever form of storage is used it must therefore promote drying. Various biochemical changes can occur to wood during storage that can affect its properties. These changes can affect the suitability of the wood for use as a fuel eg change in calorific value or particle size distribution. A suitable storage strategy will therefore be one that allows drying, but at the same time limits bio-degradation to maintain the chip quality within power plant limits.

In addition power plant operators need to understand changes in storage for financial reasons. Any loss of calorific value during storage represents a financial loss to the owner.

2 LITERATURE REVIEW

2.1 Summary

- The timing of SRC harvest in relation to the growth, dormancy and metabolite storage of the crop affects the subsequent in store changes of the biofuel. Summer crops with a full canopy have high moisture contents and high soluble carbohydrates. Bark storage proteins accumulate during autumn and winter, and decline again as spring shoot growth commences under increasing daylength.

- Wood varies considerably in composition, but all are biologically active and carry fermentative bacteria as well as varying levels of soluble, fermentable carbohydrate. Brushwood can have a chemical composition that is equally favourable to a fermentative storage process as low grade grass. In partial aerobic storage, which could be considered akin to a porous wood stack, volatile fatty acids are oxidised with the liberation of heat. In the absence of specific preservation activity this oxidation of organic acids occurs to varying degrees in wood heaps.

- Passive pre-drying by using the endogenous stack heat produced during storage could be used to reduce moisture levels if the factors affecting its production were fully understood. These factors will be affected by stack composition and structure and the dynamics of endogenous and exogenous moisture fluxes.

- Mixed hardwood and softwood have shown average moisture of the samples from 4.5m inside a stack to decreased to about 35% where moisture from rain had not affected moisture contents. With the prevailing relative humidity levels in the UK the equilibrium drying point could be within the acceptable range of moisture contents for ARBRE type plants, *provided* moisture levels are not increased by excessive rain.

- Stack temperature depends on the type of material, the particle size, the moisture content, the season when cut, the age when cut, the location within the pile, and the pile size and shape. Weight and energy loss represented by the temperatures rises are thus a complicated function of many variables. If the material is already chipped characterising the material quickly at reception is an important part of stack management and inventory control.

- The water soluble carbohydrate levels of SRC going into store can be about three times higher than those in forest residues. In the normal course of events these would fall as respiration consumes carbohydrate which is not replenished through photosynthesis. Chopping the material and putting it into bulk stores releases sugars which can ferment to produce volatile fatty acids (VFAs), alcohols and water, with the release of CO_2 and heat.

- At $65^{o}C$ it is hot enough for acetyl groups attached to the cellulose to be split from the chain to form acetic acid. In short rotation coppice bacterial interaction with sugars may also have produced other VFAs, and results from this study show lactic acid to be the most abundant VFA in the early stages of storage, and most abundant in chips from SRC rather than forest residues.

- The production of VFA (esp acetic) appears to be a natural part of decomposition of outside chip storage, and hardwoods can produce more acids than softwoods. Higher soluble carbohydrates and increased cellulose break down under low pH could assist this

- Sapwood, including the cambium, decays more rapidly than heart wood. This has implications for the storage of SRC. Whole tree trimmings lose more weight than debarked chips during storage, and whole tree chips are the main components of yard trimming composting and mulches. The dead xylem 'wood' material has a lower concentration of water soluble carbohydrates than live cells of the cambium and phloem

- Further detailed studies of the impact of the crop and stack biochemical process are justified in order to make stack management less haphazard. Once fully understood management techniques can be developed to harness these changes to contribute to passive drying processes whilst minimising dry matter and energy losses.

2.2 Glossary

ADP: Adenosine diphosphate

ATP: Adenosine triphosphate

ARBRE: An 8MW gasifier power generation plant at Eggborough in Yorkshire, run by First Renewables Ltd. It is designed to be fuelled by wood chips from short rotation coppice and forest thinnings.

Homofermentative lactic acid bacteria: bacteria which ferment hexoses predominantly to lactic acid

Heterofermentative lactic acid bacteria: bacteria which ferment hexoses and pentoses to lactic acid and other products like ethanol and acetic acid.

NIRS: Near Infra-Red Spectroscopy - an analytical technique that uses the changes in the near-infra red spectrum reflected from a sample of the material being analysed to characterise the material through comparisons of the spectra with those produced from standard samples.

NMR : Nuclear Magnetic Resonance - an analytical technique that uses a magnetic field to produce a resonance signal from hydrogen atoms in the sample, and by comparisons with known standards uses the signal to characterise the material under test.

VFA :Volatile Fatty Acids - lower order (short carbon chain) fatty acids like acetic, lactic, propionic, and butyric that are volatile at ambient temperatures. They have characteristic strong astringent smells.

2.3 Objectives

There have been many reviews of wood storage, and wood drying has a wide literature of its own. Beyond Forestry and wood sciences, agricultural science has an extensive literature on the fermentation processes for ensiling and safe storage of forages. This literature review looks for the common ground between these two disciplines and attempts to put forward suggestions for processes that combine safe fermentation, passive drying and the production of wood chip biofuels that provide consistent fuels for combustion or gasification, albeit at moisture contents that may require additional, but feasible pre-drying. The review has been prepared with particular reference to the ARBRE BIG-CC power plant.

Part of this report was to review laboratory records. These have turned out to be few and very much related to dry matter and energy content. The results of the present study will provide a far more comprehensive data set relating dry matter and energy content to the biochemical changes occurring to the stored material.

2.4 Storage studies

Kofman and Spinelli (1997), concluded that storage of willow from short rotation coppice is very difficult; fine chips, such as produced by Class and Austoft machines are not suitable for storage over prolonged periods of time (more than 2 months); fine chips loose a large amount of dry matter and a lot of their lower heat value; fine chips can also have a heavy infestation of micro-organisms. In their view SRC is best delivered straight to heating plants during harvest; if it is to be stored it should be done as whole shoots or large chunks; if it has to be stored as chips for more than 2 months then these chips should be sealed as airtight silage. With such material, long term stable storage with some internal stack drying may be an elusive target. However, the relatively high proportion of cambium tissue in short rotation coppice, and its often relatively active biological processes, mean such storage may be more capable of producing stability through low pH.

The timing of SRC harvest in relation to the growth, dormancy and metabolite storage is a further complicating factor. Summer crops with a full canopy have high moisture contents and high soluble carbohydrates. Coleman *et al* (1993) have shown bark storage proteins to accumulate during autumn and winter, and to decline again as spring shoot growth commences under increasing daylength. The timing of harvest can thus determine the balance between fermentable carbohydrate and protein, and the prevailing moisture content.

If natural soluble carbohydrate levels are low, successful fermentative storage needs high levels of natural or added bacterial inocula to produce a speedy fermentation to use up oxygen and lower pH. Interestingly forage harvester type machines used in the above study have been shown to be an excellent source of lactic acid bacteria when used in making grass silage (Henderson, McDonald and Woolfold 1972). The bacterial infestation of machinery will tend to be governed predominantly by the bacterial ‘substrates’ in the material being harvested.

Wood chip storage has been investigated at various levels for many years. In-stack temperatures of around 70^{o}C were reported in 1932 from a study at the Forest Products Laboratory in Vancouver, (Buggeln 1999). Yet despite this long period of study the work has struggled with the wide range of factors that can affect storage. These include

- Stack size and the effects on the store 'microclimate'
- Stack size heating and fire risk
- Composition of the material - hardwood, softwood, leaf and litter fractions, initial moisture
- Size and fraction distribution of material
- Method of stack loading - compressed or loose
- Covered or open stacking
- Weather - rainfall, temperature and solar input

All these factors interact with the chemical composition. When the composition of material is sub-optimal for the rapid production of low pH storage conditions it is important that storage conditions are modified to address this. In doing this can the management of stacks be conducted in such a way that moisture levels fall rather than rise? Can the losses of calorific value (CV) be minimised, and the risk of fire from heating and spontaneous combustion be removed?

2.5 Fuel quality requirements

Power generation plants can use waste heat to pre-dry wood fuel to the required moisture. For the ARBRE plant the design input moisture level prior to pre-drying and gasification is ideally 20% wet basis or less, to maintain the calorific value of the fuel gas at a level acceptable for firing into the gas turbine (Livingstone 1997). Various studies have been carried out to look at different regimes for pre-drying fuel (Livingstone 1997, Nellist *et al* 1993). Active pre-drying carries a cost for the power/heat loss required to dry the fuel at input, or additional input of time, power and effort to build dryable stacks. The capacity of a pre-drier can also limit the loading rate if moistures are excessively high. The specified maxim moisture content before the drier is 30%. However the drier system should be able to handle up to 40% moisture but with decreased overall plant efficiency. The post drier, pre-gasifier moisture content should be 10%. (Weekes, personal communication).

Passive pre-drying by using the endogenous stack heat produced during storage could be used to reduced moisture levels if the factors affecting its production were fully understood. These factors will be affected by stack composition and structure, and the dynamics of endogenous and exogenous moisture fluxes.

2.6 Stack size

A wide range of store sizes have been studied. Lamond *et al* (1993) use sealed bins of only 0.1 m^3 to study the effects of sealed storage on freshly cut Sitka spruce. The monthly losses they report are in the table 1 below.

	% DM loss $month^{-1}$	% Energy loss $month^{-1}$
Sealed	1	2.9
Unsealed	2	2

Table 1. Dry matter losses from comminuted Sitka spruce in sealed and unsealed storage

These values compared favourably with losses of around 3% for larger open stacks with lower initial moisture content. Studies of the outside storage of chips have showed a correlation between stack temperature and wood rotting. Gjolso (1991) studying the effects of biodeterioration in piles of whole-tree chips from recently fallen trees showed total weight loss to range from 6% to 20% at various points in the storage heap, with a clear correlation between temperature, microflora and loss of wood substance.

Buggelen (1999) reporting the work of Bergman and Nilsson, showed the temperature profiles in stacks 30m high. Heat loss was from the top and sides of the stacks, with the temperature towards to top and centre of the pile reaching in excess of 60^{o}C. The upward movement of heat and moisture produces a "wet lens" of moist, lower pH material where water leaves the top of the stack. The lower 5m layer of the stack never exceeded 50^{o}C.

This variation of temperature and the reduction of moisture levels within the stack has been reported by Nicholls and Feng (1992) who studied changes in a 30ft high, 450 tonne pile of mixed hardwood and softwood that was stored for 3.5 months from January 1990. Samples were taken from the surface, 7ft, 15ft and 20ft from the surface. Average moisture of the surface chips increased from less than 50% to about 65% (wet basis). Average moisture of the 15ft samples decreased to about 35% by the end of the study. Higher heating values showed very little variation. Preliminary dry matter samples from the stacks in this study showed a similar pattern of moisture loss.

The requirement for cover is a more complex problem. Nurmi (1991) in a comparison of two 3000m^3 loose piles showed chips stored under a plastic cover had greater losses and higher moisture contents than stacks open to the weather. Plastic covers are impervious and would retain both moisture and heat, the dissipation of both being important for effective drying.

2.7 Heating and the risk of fire

The fermentation and microbial decay processes of stored wood cause increases in temperature. Pile temperatures can reach 66^{o}C after just two weeks (Anon 1998) with a wide range of factors affecting the heating rate. These include pile height; a low surface to volume ratio and low radiative and convection losses; the age of the wood chips (older and more compacted); low air flow, and the presence of impurities such as bark, decayed wood and sawdust. Fine, blown wood chips or pneumatically conveyed wood chip piles are more vulnerable to spontaneous combustion since the fines are separated and stratify in a way that reduces heat dissipation. The use of computational fluid dynamics in the present study will attempt to evaluate how heat moves through wood chip heaps.

As the volume of a stack increases roughly by x^3 where x is the linear dimension, larger stacks can generate more heat for the available radiative area unless some thinning, or flattening of one or more of the faces of the stack is undertaken. The figure below (Fuller 1985) shows how higher stacks produce, or at least retain higher internal temperatures.

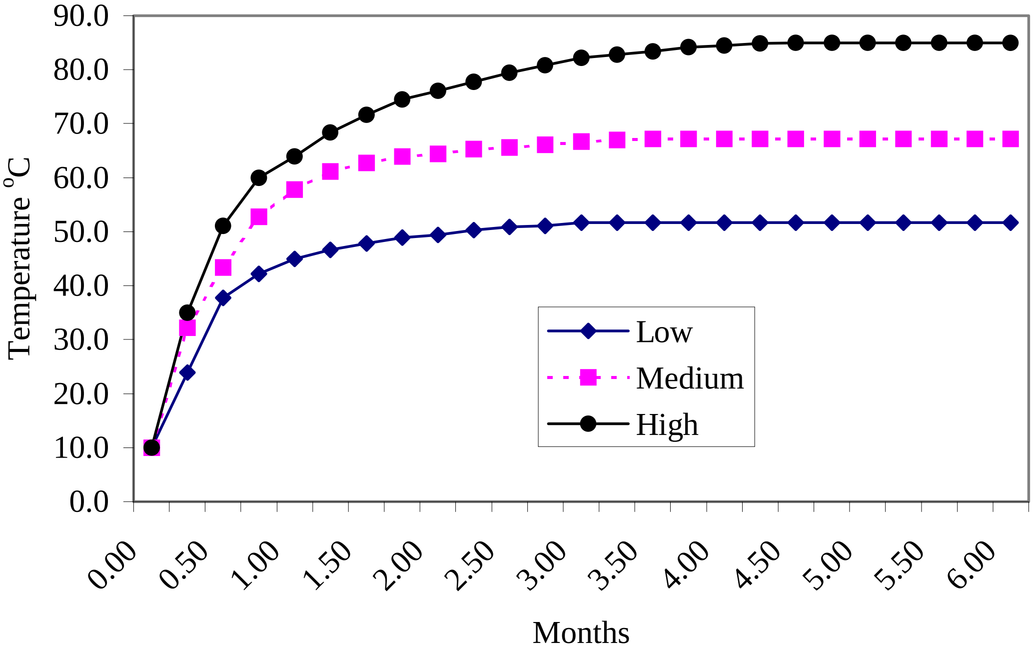

Figure 1. The effect of stack height on temperature

In Figure 1 above the initial temperature increments in the first two weeks of storage are attributed to ray cell respiration, and are followed up at around 40 days by an increase in bacterial activity and then fungi. The potential for spontaneous combustion exists in the tall stacks with high compaction. The low stacks with low compaction can stay below *c* 54°C, the temperature at which autoxidation starts.

The avoidance of high stacks in storing wood chip is further endorsed by the fire authorities in Ontario (Anon 1988), with recommendations that piles should not exceed 18m in height. They further recommend limiting the width to 90m and the length to 150m. Whether the latter relate to avoiding a large combustible single mass or to lessening the contribution to heat production is not clear.

Fuller (1985) usefully reviews the changes that contribute to temperature rises; during the first week living cells are contained in the bark, foliage and wood when the tree is cut. These remain viable for long periods of time when wood is stored in log form - up to six months in certain conditions. Fuller's review is based on the requirements of the pulp industry where most of the bark and foliage are removed in the preparation of pulpwood. The scope for more rapid respiration and subsequent changes in SRC chips should not be overlooked. When the wood is chipped the living cells in the wood initially respond by trying to heal the damage; the respiration increases and heat is released. In deep compacted stacks there is more wood to heat up, and dissipation of the heat is reduced. The heat generated provides good conditions for bacterial development which can feed on the soluble extractives of wood. At the end of a 7-14 day period stack temperatures can commonly be just under 50°C.

During weeks 2-5 of storage the events are largely influenced by factors that limit air circulation in the stacks. Deep piles that are compacted or have a high proportion of fines have low circulation rates (Springer and Hadjny, 1970). As the heat dissipates only slowly temperatures can reach around 65°C. At this point it is hot enough for acetyl groups attached to the cellulose to be split from the chain to form acetic acid. In short rotation coppice bacterial interaction with sugars may also have produced other volatile fatty acids (VFA), and initial results from this study show lactic acid to be the most abundant VFA in the early stages of storage, and most abundant in chips from SRC rather than forest residues.

2.8 Moisture - acceptable fuel

The comments at the start of this review put acceptable fuel as ≤ 20-30% before going into the pre-drier at the ARBRE gasifier power plant. To be acceptable from a non-ventilated store these moisture levels need to match or be below the equilibrium point for the prevailing relative humidity. Nellist *et al* (1993) fitted a range of equations to drying spruce or birch chips which showed the equilibrium points for between 20% and 30% chip moisture content to fall typically between 80% and 90% relative humidity. With the prevailing relative humidity levels in the UK the equilibrium drying point would therefore be within the acceptable range of moisture contents for ARBRE type plants, *provided* moisture levels are not increased by excessive rain.

2.9 The composition of wood chips

2.9.1 Harvested material

The chemical composition of wood chips is important in determining their behaviour when stored in large piles or stacks. Elsewhere in this review analogies are made between changes in grasses during ensilage and the changes undergone by wood chips stored in stacks. The harvesting and handling logistics of the two systems differ, so direct comparisons should be treated with caution, although some aspects are worth pursuing. Chum, Milne, Johnson and Agblevor (1993) in reviewing chemical composition of feed stocks give the values shown in Table 2.

	Softwoods	Hardwoods	Grasses
Cellulose	41 - 43	43 -45	35 -39
Lignin: ave (*Range*)	28 (*24-33*)	22 (*16 -24*)	16 (*15-18*)
Xylan: (*Pentosans*)	8 -14 (*5 -10*)	20 -30 (*12 -24*)	27 -34 (*25 -29*)

Table 2. Chemical composition of typical lignocellulosic materials (%)

To get rapid and effective fermentation that can give some stability to storage conditions requires adequate fermentable carbohydrates. In wood chips lignification, to varying degrees, restricts the accessibility of celluloses and hemicelluloses that can be broken down bacterially to supplement pentosans, which like lignification vary across the different sources of wood. Delignification is more difficult in softwoods, and the opening up of the cell wall structure providing access to the cellulose is more of a problem. On average softwoods have less total carbohydrate, slightly less cellulose than hardwoods and less pentosans available. Hardwoods have a higher acetyl content than softwoods and most grasses, and would yield more acetic acid. At their higher levels pentosans in hardwoods approach those found in grasses, so the addition of bacterial inocula could provide a way to have more controlled acidification if stack conditions can be made suitable. The pentosan levels in softwood are low enough to preclude rapid initial pH changes on storage, although the greater lignification may reduce the efficacy at which hemicellulases can produce xylans.

The difference in the storage characteristics of hardwood coppiced material, with a higher cambium to sapwood ratio than more mature large trees, and softwood forest residues (that have spent time in situ, in producers storage or in transport), means there will be significant differences between the storage characteristics of SRC chips and forest residue chips, especially if the latter are softwood. Storing and handling the two materials in the same way is likely to give sub-optimal storage for one or other of the materials, if not both.

2.9.2 Chemical changes - storage losses

Most of the work done on wood chip storage has been done by the paper industry where the retention of cellulose fibre and freedom from discoloration are important factors (Fischer, 1991). When sufficient amounts of active peroxidase, malate dehydrogenase and oxygen are present as in beech wood chips, the wood is discoloured by the formation of chromophores. Discoloration of fuel is little significance if that discoloration is not accompanied by an energy loss. Mixed wood chips stored locally prior to their use the ARBRE power plant showed discoloration which was clearly visible, whilst olfactory assessment indicated that there had been some formation of volatile fatty acids. Analysis of the material is shown in the second column of table 3. Along side the data are values from material delivered to store at the start of the present study.

Component		**SRC**	**Forestry residues**
	12 month storage	As delivered to store	
pH	3.2		
Oven Dry matter	57.3	50.4	64.0
Water soluble carbohydrate (%)	n/a	1.94	0.68
Acetic acid (mg/kg)	5440	<325*	<325
Lactic acid (mg/kg)	527	5774	1586

** Arbitary lower sensitivity cut-off*

Table 3. Composition of samples taken after long term storage, and as delivered to store from harvested SRC and Forestry residues

The level of lactic acid relates directly to soluble fermentable carbohydrate in the wood mass where its production is via homofermentative or heterofermentative lactic acid bacteria. MacDonald (1981) cites various reports supporting glucose/fructose changes to lactic acid due to the action of homofermentative bacteria as

$$C_6H_{12}O_6 + 2ADP \rightarrow 2CH_3CHOHCOOH + 2ATP \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..1$$

One glucose or fructose mole giving rise to two moles of lactic acid via two pyruvate molecules. Where pentoses derived from hemicellulose are fermented via homo- and heterofermentative lactic acid bacteria one mole of acetic acid is produced along with one mole of lactic acid

$$C_5H_{10}O_5 + 2\ ADP \rightarrow CH_3CHOHCOOH + CH_3COOH + 2\ ATP\ldots\ldots..2$$

The environment in wood chip piles is probably much more variable than is silage stacks. The chips size and proportion of fines will alter the movement of air and heat through the stack and most bacterial fermentation will be aerobic; pentoses from cellulose and hemicellulose giving rise to lactic acid, acetic acid, water and CO_2. It is interesting to note that Jirjis (1995) pointed to the presence of volatiles as source of error in dry matter determinations on stored wood chip. This has long been accepted in the evaluation of silages with dry matter being quoted after toluene distillation has been used to account for the energy rich volatile compounds that would be lost to the atmosphere with oven determinations of dry matter.

The material taken from long term storage has shown the movement to a high acetic acid status associated with chip storage from forest material. Fuller (1985), citing Kubler (1982), describing the process in compacted stacks, attributes the acetic acid formation to the cleaving of acetyl groups from cellulose molecules when the internal stack temperatures reach around 65^{o}C. This is followed by darkening of the chips, a crumbling as the cellulose structure is weakened, and a fall in pH such as shown by the sample value of 3.2. As mentioned on other occasions in this review the conditions in chip stacks are extremely variable. In general at higher temperatures, chemical reactions are most active. In lower uncompacted stacks that can dissipate heat to avoid high internal temperatures wood rotting fungi are able to slowly deteriorate chips after the initial heat rise has passed and temperatures drop below 50^{o}C (Bergman 1974). (*See also section on fungal decay*)

But do SRC chips behave in the same way as chipped forest residues or whole wood chips destined for pulp manufacturing? When wood is harvested, and particularly short rotation coppice there can be high levels of live bark and leaf tissue along with soluble carbohydrate in the sap. The water soluble carbohydrate levels in SRC (table 4), for material going into store about three times higher than those in forest residues. In the normal course of events these would fall as respiration consumes carbohydrate which is not replenished through photosynthesis. Chopping the material and putting it into bulk stores releases sugars which can ferment to produce VFAs, alcohols and water, with the release of CO_2 and heat.

2.9.3 Dry matter losses

Wood, and particularly the relatively young rods of short rotation coppice, is a biologically active material. Unlike fossil fuel it undergoes changes during storage. To date, studies of stored chips have been designed to either look at losses prior to moist chips being processed in pulp making plants, or to look at the efficacy of drying processes prior to combustion. Using energy or disruptive storage logistics, which add cost to a fuel, reduces the financial competitiveness of biofuels where one of the main requirements is to achieve the lowest cost per unit of lower heating value. However desirable it may be to support biomass based power generation through various forms of subsidy, physical and economic efficiency must be the main drivers for long term adoption of the technology. This review is being produced before the data from the DTI funded study of energy use in the fuel supply chain has been completed. One aspect not addressed is the possible need for the design and construction of combustion/pyrolysis units with capacities to cope with higher moisture fuel at loading.

There is a correlation between pile temperatures and wood rotting, the rate of biodegradation of organic matter being a function of temperature (Buggeln 1999). Temperatures of 66-72^{o}C were recorded in an open pile. Hakkila (1989) maintained that respiration increased with temperature up to 40^{o}C, and the optimum temperatures for aerobic deterioration are around 20^{o}C to 30^{o}C. Fungi and bacteria need a source of nitrogen which can be derived from bark, cambium and foliage.

After green wood is chipped the living cells in the cambium continue to respire, but this process may not last very long. As green wood is chipped into small pieces chemical reactions occur immediately as cell chemicals are exposed to air. When these reactions occur, Feist (1973) showed that greater wood degradation occurred when microbe-free wood chips were simply heated to 65^{o}C compared with 55^{o}C. Thus temperature alone accelerated the degradation of wood chips, at least as measured by the loss of chemically fragile components. Heat accumulation in stacks, and its active and rapid dissipation is therefore something to be aimed for in stack management. According to Edwards, cited by Nellist *et al.* 1993, tall compacted stacks of forest waste contain the heat and reduce natural air movements, producing temperatures of 60^{o}C or more. In contrast uncompacted heaps appear not to rise much above 40^{o}C as natural air movement through the pile is sufficient to dissipate the heat.

Notwithstanding these heating effects the greatest losses occur in the hot, moist interior parts of the stacks. Dry weight and specific weight loss can show this.

The nitrogen in bark and cambium is the main source of organic N for fungi attacking whole tree (xylem) wood (B. Henningsson in Buggelin 1999). The N content of bark is three to eight times higher than wood. Adding N to stored sawdust and bark increased the rate of breakdown and CO_2 production, although when grown in culture wood decaying fungi preferred organic rather than inorganic nitrogen

Sapwood, including the cambium, decays more rapidly than heart wood. This has implications for the storage of SRC. Whole tree trimmings lost more weight than debarked chips during storage, and whole tree chips are the main components of yard trimming composting and mulches. The dead xylem 'wood' material has a lower concentration of water soluble carbohydrates than live cells of the cambium and phloem, Pate (1975).

Buggelin's review (1999) suggested "a rule of thumb" of one percent wood loss per month in outside chip storage. In billet storage experiments in covered bins using poplar and willow, Rushton (1999) reported dry matter losses over a nine month period of 11.9% and 5.7% respectively for the two species. A mean loss of 1% per month. Uncovered poplar and willow sticks had mean dry matter losses of 15.7% and 4.3% - a mean of 10% over the nine month period. Jirjis, citing Nellist *et al* (1994) showed monthly dry matter losses of approximately 1%, 2%, 2% and 6% from drying, evaporative cooling, cooling and unventilated storage of 12.5m^3 batches of willow. The "rule of thumb" was again showed to be a durable figure in Norwegian work (Gojlsjo, 1994) again cited by Jirjis, where comminuted birch stored for eight months lost 9.7% dry weight in a large pile and 7.5% in a small pile. A high proportion of living cells contributes to greater losses in store. Sanderson, Egg and Wiselogel (1997) showed dry matter losses of 13% over six months from material baled in August (58% dry matter, 20% green leaf, 5% dead leaf) and about 5% for material stored over 12 months after baling in November (56% dry matter, 15% green leaf, 19% dead leaf). So although the 1% "rule of thumb" value seems quite a reliable generalisation for losses, the causes of those losses are varied.

2.9.4 Respiration losses

Nellist *et al* (1993) suggest a 1% dry matter loss (10g / kg dm) is equivalent to a loss of 160kJ / kg dm. If this was used within the stack to evaporate water with a latent heat of vaporisation of 2500kJ / kg this would represent 160/2500 or 0.064kg water / kg dm ie 6.4% dry basis. For material at 50% moisture content it would be reduced to 48.3% wet basis. If the heat value of the dry matter is unchanged the loss of energy value of an original 1kg DM would be 190kJ, *c* 1% of the total gross energy. On this basis, in the event of respiratory heated drying without rewetting over a 12 month period, the “rule of thumb” 1% dry matter loss per month would result in 12% less material after 12 months but with a 20% drop in moisture.

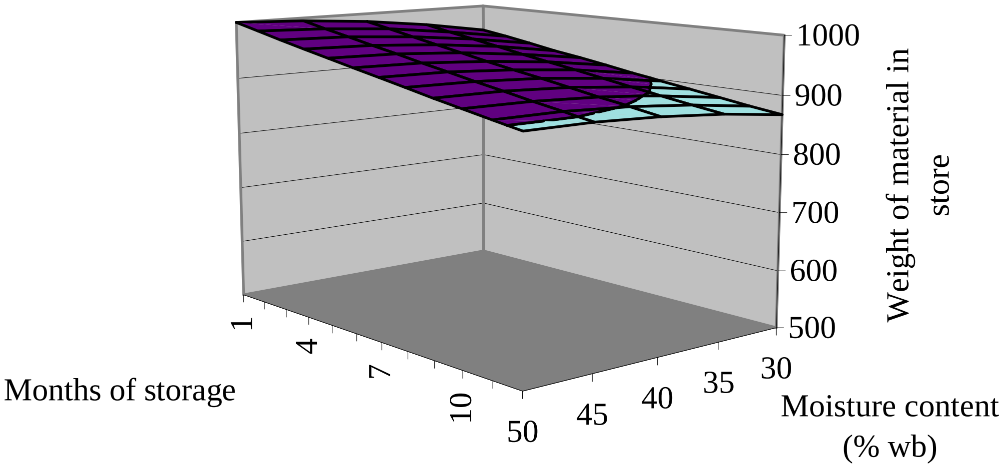

Figure 2. Schematic diagram of weight loss due to drying and dry matter loss over 12 months

Over a 12 month period the 12% loss in dry matter could be associated with a reduction in the moisture content from 50% to 30%. Figure 2 shows that after a year there would be 867 tonnes of material at 30% moisture left from the original 1000 tonnes at 50% moisture.

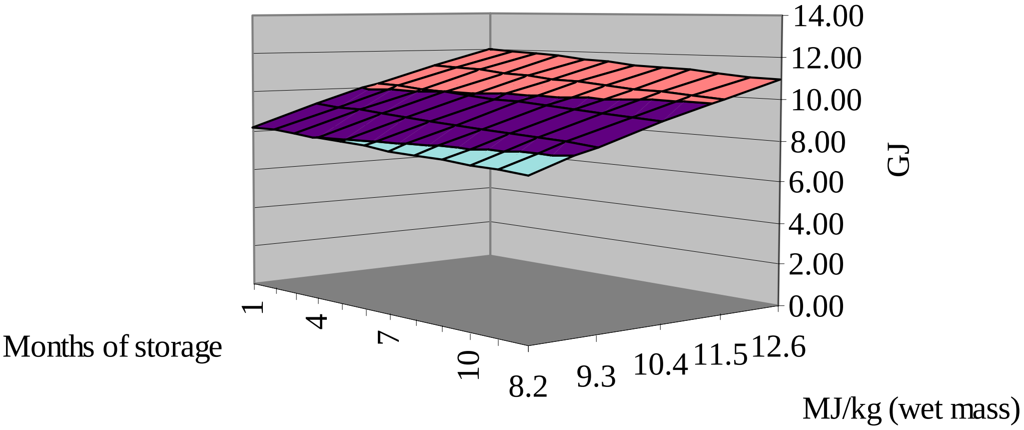

Figure 3. Schematic diagram of changes in total net energy arising from drying and dry matter losses over a 12 month period

However the material at 30% moisture would have a higher net energy per unit of wet mass than that at 50%, which would off-set the loss of weight due to drying, and partially off-set the dry matter losses. The total net energy in a tonne of the materials in figure 2 are shown in figure 3 above. The net energy values are derived using

NE = 19.2-0.2195*moisture content (wet basis).......(Nellist *et al*,1993)

2.10 Fungal breakdown - decay

The production of VFA (especially acetic) is a natural part of decomposition of outside chip storage, and as mentioned above, hardwoods with more pentosans and higher acetyl components than softwoods can produce more acids. Buggeln (1999) quoted "laboratory experiments" showing hardwoods to be more susceptible to soft rot fungi than coniferous species. Higher soluble carbohydrates and increased cellulose break down under low pH could assist this, provided high fungi- and bacteria-suppressing stack temperatures are avoided. Resins and turpentines in coniferous material may also act as deterrents to soft rots. Fungi development in large stacks is affected by temperature, moisture, the degree of aerobism and the length of storage period.

Most wood rotting fungi (white and soft rot) show the greatest activity between 25^{o}C and 45^{o}C, with an optimum in the mid 30’s, and are thermo tolerant rather than thermophilic. However, despite the variation in fungal infestation Hellenbrand and Reade (1990) asserted that wood chips are almost never free of potentially harmful microbial species, and recommended that suitable protective clothing and respirators are used.

The similarity of the biological dynamics of wood stacks to silage is furthered by the comments of Springer and Hajny (1970) who commented that variables do not act independently of one another. The type of microorganisms present in a given situation depends on both the type of material present and the prevailing temperature. Temperature in turn depends on the type of material, the particle size, the moisture content, the season when cut, the age when cut, the location within the pile, and the pile size and shape. Weight and energy loss are thus a complicated function of many variables. Characterising the material quickly at reception is an important part of stack management and inventory control, if the material is already chipped.

The issue of where and when to chip relates more to forest waste than SRC. Jirjis (1995) cites results of storage trials of uncomminuted logging residues, in covered windrows or bundles, from both fresh and summer-dried material. They showed many advantages compared with chip storage. The risks of self ignition and allergic reactions were eliminated and dry matter losses were minimal. However, recent harvesting experience in the UK suggests that with the soft flexible wood of SRC the logistical advantages of high speed chip harvesting with existing well developed forage based machinery reduce the attraction of separate operations for harvesting and chipping the rods.

Chipped and dried timber is not without its problems. Jirjis commented that the moderate temperature during the storage period in a ventilated pile (last six weeks 25-50^{o}C) facilitated substantial fungal activity on chips despite the extremely low moisture content (15%).

Wet SRC at 57% was stored for 11.5 weeks in small bins and moisture dropped to 19.3, 42.0, 47.7 and 44.9% in the treatments drying, evaporative cooling, cooling and unventilated control. Corresponding dry matter losses were 3.5, 7.1, 7.9 and 19.1% of the harvested dry matter. It is noteworthy that the moisture levels in the bins were higher than the internal stack dry matters observed by Nicholls and Feng (1992) and in preliminary data from this study

Particle size has a significant and long lasting effect on stack temperature and thus the consequent biochemical processes. In Denmark, *Pinus contorta* was stored as chips (*c.* 16mm), fine chunks (*c*. 50mm long) large chunks (150mm long) and firewood (250mm long) (Kofman 1994). After a year’s storage heat generation in the two larger sized stored materials was mostly dependent on ambient conditions. Temperature development in the finer particles was higher and less dependent on ambient conditions. Better drying was observed in large particles with a 9.5 % reduction in moisture. The average moisture in the chips was marginally changed, whilst chunk wood fell, from 34 to 29.5% (wet basis). Chunk cutting rather than fine comminution presents some problems with high throughput chopper/blower systems based on forage harvesting power trains.

Should the development of storage techniques relying on low pH and controlled oxidative drying of stacks not be feasible anaerobic storage has been shown to be a technique that could guarantee the delivery of homogenous wood chips (Kofman *et al* 1999). Three batches of *Picea abies* were stored airtight with one control batch. The airtight storage gave no redistribution of moisture, low dry matter losses, unfavourable conditions for microbial activity of most fungi and the promotion of yeast instead of fungi with airborne spores. As a result of these successful tests larger scale evaluation was planned.

2.11 Scope for storage with passive drying

Can the fermentation products of stored wood chip provide a stable medium term storage environment in much the same ways as millions of tonnes of conserved forages are stored as silage? The success of silage making depends on producing an anaerobic storage mass and on the rapid formation of volatile fatty acids (ideally lactic, but also acetic and butyric when poor fermentation conditions prevail). The rapid production of these acids is achieved by having high levels of sugars in the conserved material, or when sugar levels are low by adding additives that cause a rapid drop in pH or act as preservatives. Molasses was one of the first widely used additives, to be followed by organic acids which in turn were superseded by their salts and more recently by microbiological agents such as lactobacilli cultures.

Wood varies considerably in composition but they are all biologically active and carry fermentative bacteria as well as varying levels of soluble, fermentable carbohydrate. The figures below (Anon 1976) compare brushwood and grasses of low and high digestibility. High digestibility silage is stored successfully as silage and most livestock farmers have mastered the practical requirements needed to ensure stable storage. Low digestibility material with lower levels of rapidly fermentable carbohydrates causes more problems at ensiling, and additives that assist with the rapid lowering of pH are more commonly needed. In aerobic storage, which could be considered akin to a porous wood stack, volatile fatty acids are oxidised with the liberation of heat. In the absence of specific preservation activity this oxidation of organic acids occurs to varying degrees in wood heaps.

The figure 4 overleaf shows that despite there significant differences in form it could be argued that brushwood at least, has a chemical composition that is equally favourable to a fermentative storage process as low grade grass. In many cases wood is more heavily lignified and thus hard to store with air excluded, but once comminuted at harvest this difference is reduced. Most of the nitrogen free extractives in wood are derived from polysaccharides like hemicelluloses and starch and to a lesser extent pentosans, whereas in grass the bulk of the active drivers of ensilage are rapidly fermentable sugars. The lower nitrogen content of wood, in theory, should reduce the rate of break down (Allison and Murphy 1962), although this may be offset by the generally more aerobic conditions. Overall the above compositional figures are sufficient to raise the possibility that some form of controlled fermentative/anaerobic storage is a possibility.

	Brushwood	Grass (low digestibility)	Grass (high digestibility)
Crude Fibre (*cellulose and lignin*)	356	380	305
Nitrogen Free Extractive (*starch, sugars, etc.*)	537	345	390
Ether extract (*fats, waxes,resins*)	25	35	40
Nitrogen	10	26	27

Table 4. Comparison of proximate analyses of brushwood and grasses (g/kg)

The possibility of using this type of fermentative storage is partially supported by the work of Johnson *et al* (1994) in which four woody and six herbaceous species were harvested at different times, and changes that occurred during unprotected storage of between 26-52 weeks were reported. Only small changes (<3%) were seen in the quantity of structural components: cellulose, hemicellulose and lignin. The largest changes were observed in material that could be extracted with 95% ethanol. These extractives are a relatively minor part of the plant mass and contain non-structural material, although the breakdown of structural material can lead to formation of soluble extracts. Decreases of up to 70% of the original levels of extractives have been recorded.

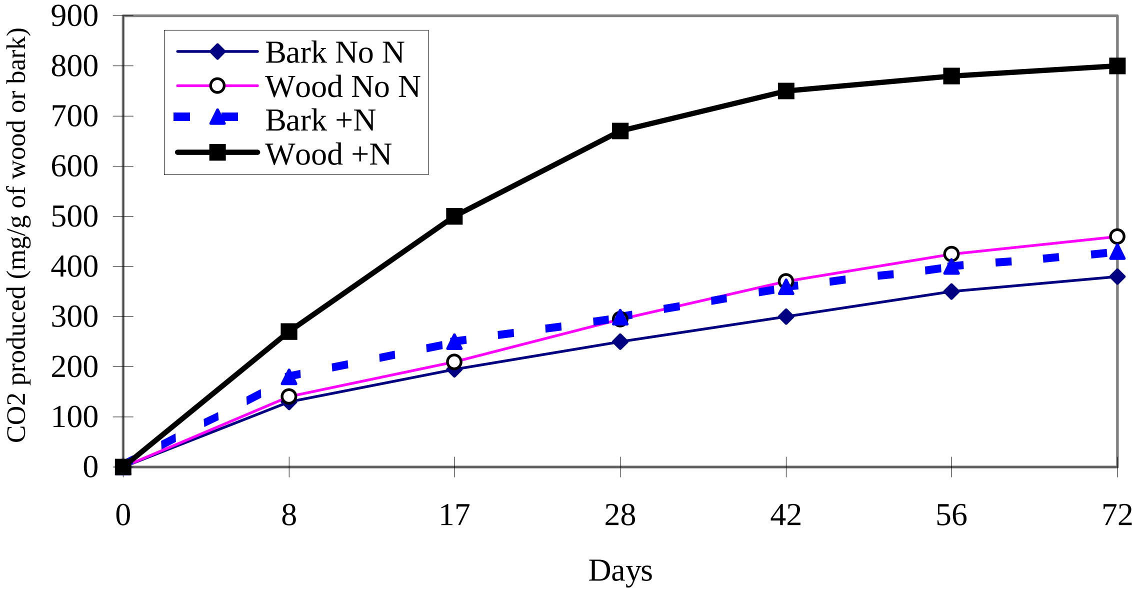

Figure 4. The effect of nitrogen on respiration losses

If extractives can be stabilised by fermentation to produce a stable low pH, and the breakdown processes of structural components which add to the level of extractives, reduced, then the store will have some longer term stability. If, subsequently the store is managed to allow 'controlled' oxidation of the acids, then endogenous heat, solar heat and wind evaporation, along with minimised retention of rainfall will move the stored material towards the goal of minimised energy loss, with passive moisture loss during storage. The soluble carbohydrates will have provided the initial preservation and the energy for the subsequent internal drying process. Clearly much more information and development is required to develop such as system.

2.12 Implications for plant design

Fuel with higher moisture content has a lower net calorific value (*see fig. 3*) that reduces the overall plant efficiency. If it comes out of store at higher moisture contents than the design moisture loading of the plant, pre-drying costs have to be increased with a drain on the generated output. Alternatively the design criteria for gasifiers and furnaces can be modified depending to use lower grade heat from the additional condensate. Such an approach has been taken in a generation plant at Oslo International Airport (Anon 2000) and clearly shows how biomass up to 65% moisture can be used.

2.13 Waste in store and Inventory strategy

Where large tonnages of material are stored whether it be fuel, or chips for pulping, the total cost of the fuel to the business is made up of the basic cost of the material; storage losses (various aspects of which have been reviewed here and are main subject of this study); pre-combustion waste either direct loss or as a consequence of the storage method adopted, and interest charges on the cost of the fuel prior to the power or pulp being sold.

Part of this study looks at the early determination of storability using NIRS assessments. Gillon, Joffre and Ibrahima (1999) using pteridophyte and grass litter showed significant correlation between incubated litter decomposition and the NIRS values. Although the litter composition differs slightly from woods, (the figures in table 4 are representative of the difference) the adoption of such a technique would allow better inventory management with the most storable material being stored for the longest periods. Wiselogel and Agblevor, (1995) have used Nuclear Magnetic Resonance (NMR) for a similar purpose on SRC, and in hybrid poplar a decrease in pyrolysis oil heating value was small (4%) yet the associated structural changes were indicated by NMR. They considered changes would increase with a longer storage time or more severe storage environmental conditions. These in turn would affect the value of the stocks.

Running a low inventory to reduce storage losses can be risky if stocks run out due to unforeseen circumstances. Such stock-outs are extremely costly, and are avoided by carrying more cost tied up in the fuel inventory. The bigger the plant the more costly the stock out. The figure below was derived by Finke (1984) and although it shows the enormous stocks and costs associated with pulp factories, it shows how there is an optimum stock level A, where the inventory is optimised in terms of cost. Having too small a starting inventory increase the risk of a costly stock-out, whilst carrying excess stocks increases cost arising from interest charges and spoilage.

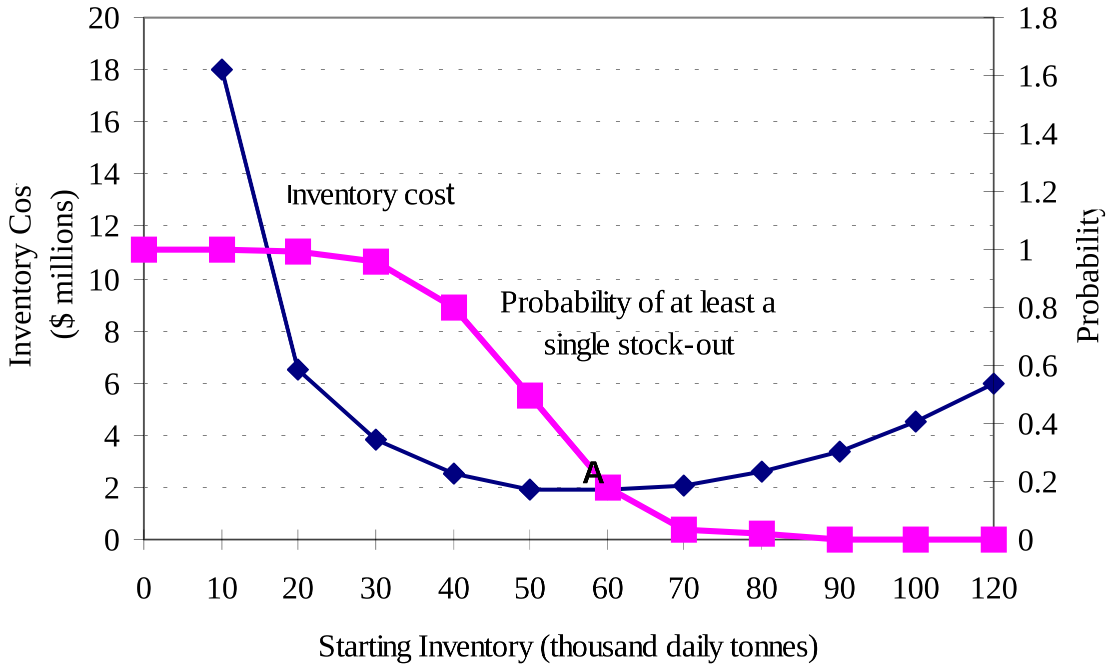

Figure 5. Example of inventory target analysis to determine optimum chip pile inventory size (After Finke 1984)

This review shows there are a wide range of factors affecting losses. The chemistry associated with the changes in store is better understood for hardwoods and softwoods, than for SRC, particularly given the impact of stack size and form, on the changes. In 1992 Suadicani and Heding commented on the fact that research into drying and storage of wood chips was approached in two ways; the pragmatic field experimenters who maintain that large scale drying is too complex a process to be effectively modelled, and the determined modellers who look to understand the natural laws which govern the drying of comminuted fuel.

2.14 Future work

In the brief look across both fields in this review some aspects appear as crucial in determining how stacks dry and justify further empirical study:

- The porosity and the capacity for conduction and convection within the stack, and factors which affect these values and their repeatability.
- The initial level of soluble carbohydrate that affects initial pH drop and subsequent heat production, and the field factors such as species, time of cutting, type of comminution and weather.
- The input of water into the stack from rainfall and the capacity of the stack to resist this whilst letting moisture escape. There are many alternative materials, stack shapes, and temporary structures that could be developed for cheap stack coverage.
- Stack management is affected by the nature of the material harvested, loading techniques, stack surface:volume ratios, and many other factors. Mixing material from different stores to optimise the fuel blend may allow progress to be made in producing self drying stacks as part of the mixed supply inventory.

The integration of knowledge of the biochemical process into the physical operations of harvesting and stack management could offer a reliable way to produce stable long storage biofuels at competitive prices.

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3 METHODS

- Pile construction
- Sampling
- Proximate analysis
- Bulk density
- Biochemical analysis: Determination of volatile fatty acids, (C2-C6), lactic acid and ethanol
- Near infra-red measurements Air flow and computational fluidised dynamics modelling
- Spore measurements and dust monitoring
- Temperature measurements
- Weather data

3.1 Pile construction

Two piles of wood chip were constructed, one using forest residues, one using willow SRC, at a storage site at Great Heck in North Yorkshire. Great Heck is located just to the south of the M62 near to junction 34. The site is an exposed ex-airfield surfaced with broken tarmac. The surrounding land is flat. The site is owned by Northern Straw and is used for storing baled straw in addition to storage of wood chip and round wood by ARBRE Energy Ltd. The forest residues came from a number of broadleaf woodland sites in the Yorkshire area at Langton, Wintringham, Kirkburn, Auborn, Newark and Callans Lane. The material consisted of low grade broadleaf material, principally beech cord-wood and brash left after the removal of the higher value stem wood during thinning operations. The wood was chipped with a Logset drum chipper and brought to the storage site by bulk tipping wagon. The willow SRC was harvested from seven sites using a Claas forage harvester with a specialised SRC header. All of the willow was in its first rotation, established four years ago, cut back after one year, and harvested in its dormant period after a further three growing seasons. The wood chips were mounded into long piles with a triangular cross-section, but were not compacted. The forestry residue pile was approximately 4.5m in height with a slope angle of 37º and the SRC pile was approximately 5.0m in height with a slope angle of 39º. The weight of every load delivered was recorded and each load was sampled to measure its moisture content.

Plate 1. Aerial views of the SRC and forestry residue piles at the Northern Straw storage site

Forestry residue pile on the left and the SRC pile on the right.

3.2 Sampling

At intervals during the trial, samples were taken from the two piles. A teleporter with bucket was used to excavate a section of the pile from the side into its centre line to reveal a vertical face.

Plate 2. Interim sampling - using a teleporter to make a vertical face in the forestry residue pile

Two 5litre samples were taken from the face at each of depths 0.1m, 0.5m, 1.0m, 1.5m and 3.0m from the top of the pile. One set of samples was sent to Innogy's central support laboratories at Drax for determination of moisture content, ash content, calorific value, and particle size distribution. The other was sent to ADAS' laboratories for measurement of various biochemical parameters. The piles were built up over a period of several weeks, so the material was not evenly aged. However, it was possible to estimate the approximate delivery date at any point along the pile, allowing the time in store of the particular material being sampled to be estimated. Each set of samples was taken from a different point along the pile so that undisturbed material was sampled on each occasion.

3.3 Proximate Analysis

3.3.1 Sample preparation - fuel

Each sample was subdivided using 10 50ml scoops, to give a 0.5litre moisture sample. The remainder was used for an analysis sample. The moisture sample was dried at 105°C and the ash sample was dried at 30°C. Further crushing of the ash sample produced a product of nominally 1mm.

Particle sizing

The sizing sample was dried at 30°C and passed through a 30mm sieve, and then through a 3mm sieve. The +30mm, -30mm and –3mm fractions were weighed and reported as a percentage of the total weight of dry sample.

3.3.2 Moisture sample

The moisture sample was placed in a shallow tray and dried in an air oven at between 105^{o}C and 110^{o}C for between 16 and 24 hours. The loss in weight as a percentage of the wet weight was taken as the total moisture on receipt. The results were reported from a single determination.

3.3.3 Calorific value

Approximately 1g of analysis sample was pelletised, weighed to 4 decimal places and burned in an oxygen atmosphere at 36bar pressure in standard calorimetric equipment. The increase in temperature was measured, and the calorific value was adjusted for acid corrections before reporting the calorific value at constant pressure, in KJ/kg. The results were reported as the average of 2 determinations.

3.3.4 Ash/analysis moisture

1g of sample was weighed accurately and heated to between 105^{o}C and 110^{o}C in a stream of nitrogen. The crucibles were frequently weighed until a constant weight was reached. The loss in weight was deducted from the initial weight and the percentage loss was recorded as the as analysed moisture content. The crucible was then heated to 550^{0}C in oxygen and weighed until a constant weight was reached. The final weight as a percentage of the initial weight was recorded as the ash content. The results are reported as the average of 3 determinations.

3.4 Bulk density measurements

The bulk density of the delivered wood chip was estimated from the delivered weight of the load and the volume of the trailer. Bulk density measurements were also made at the end of the trial to estimate the loss of dry matter during storage. A 50 litre bucket was filled with loose chip and the net weight measured. A sub-sample was taken for moisture content measurement in order to correct the density measurement to a dry basis.

3.5 Determination of volatile fatty acids, (C2 -C6), lactic acid and ethanol in wood chip samples

The sample was shaken with water to extract the fatty acids. After filtration and centrifugation, extracts were analysed by gas-liquid chromatography. The fatty acids were separated from other extracted materials, and from each other, in a chromatography column. The eluant from the column was passed through a flame ionisation detector. This generates a signal each time an organic compound elutes. The signal is related to the concentration of the eluant. Comparing the signal with standard compounds allows quantitative determination of the individual fatty acids.

Near infrared reflectance spectroscopy (NIRS)

Samples of wood chip material were prepared by grinding them through a knife-mill. A representative sub-sample was wrapped in Cling-film and transferred to a "High-fat" quartz cell. This was presented to the NIRS instrument and scanned with light in the region of 400-2500nm. The resulting spectrum from each sample was correlated with the wet chemistry data. Combining results from a number of samples enables calibrations to be developed to predict the wet-chemistry result. The success of these calibrations can be assessed by reference to the plot of wet-chemistry vs. NIRS data. Once promising equations have been established these are validated by presenting "unknown" samples to the NIRS and comparing the results with those obtained by the wet-chemistry analysis.

NIR Spectroscopy provides a rapid non-destructive means of analysing a wide range of materials. Quantitative analysis is achieved by a variety of techniques, e.g. partial least squares regression, to correlate variation in spectral features with variations in the sample chemistry. Discriminate analysis can use the unique sample spectrum to provide a qualitative analysis. Appendix 7 describes the principles of the NIRS technique in more detail. Between March 2001 and March 2002 90 wood samples (ET001A to ET090A) were scanned and analysed by wet chemistry methods for dry matter, pH, lignin, cellulose, water soluble carbohydrates, ash, and volatile fatty acids. The NIRS technique has the advantage of requiring little, if any, sample preparation so the extension of the technique for routine use at the plant weighbridge / reception facilities would be feasible. Indeed NIRS equipment is widely used for the routine testing of plant derived material for industrial/food processing.

3.6 Air flow and computational fluidised dynamics modelling

3.6.1 Density

Test samples of SRC and forestry residue wood chip were packed into a 0.78m^3 vessel and weighed. Particle size and dry matter observations were made for each.

3.6.2 Resistance to air flow

The SRC and forestry residue samples were placed in an apparatus developed for measuring bulk resistance to air flow. In the first test the direction of air movement was vertical and in the second the flow was radial. For each test the pressure difference across the sample was measured at a number of different air flow rates. The pressure gradient in the radial tests was converted to the equivalent horizontal parallel flow pressure gradient by a geometric transformation of the observations. All the observations were fitted to a power law function.

3.6.3 Air flow, heat flow and dry matter loss

The scale of the project did not allow practical study of the distribution of dry matter loss or heat and air flow in the storage heaps. A simple modelling approach was instead used to develop an understanding of the heat and mass transport processes and to create a tool that could be used to produce practical storage design guidance. The overall aim is to minimise dry matter losses and the development of dangerous moulds.

3.6.4 The model

Most storage piles have a constant cross-section and are much longer than they are wide. A two dimensional model was chosen to represent a typical cross-section of the bulk. The cross-section was divided into a few (up to 20) quadrilateral elements. The properties of each element can be independently specified as can all the boundary properties. In each time step a steady state heat flux is assumed and the rate of change of dry matter, moisture content and temperature of the element is calculated. Continuity requires that air flow into and out of any element must sum to zero and that the same constraint must apply to the heap as a whole. The surface boundary conditions can be linked to typical ambient temperature and humidity. The interface could be developed in the future to investigate the influence of wind pressures on heap behaviour.

The model predictions are based on convective air movement. The rate of heat production by the stored material generates the driving force for this process. A respiration model developed during a previous study of short rotation coppice storage (Nellist 1997) was modified to reflect the decrease in metabolic activity with length of storage. A simple decay function which described the decrease in water soluble carbohydrate with storage time was used to modify the respiration rate intensity.

The model predicts the movement of heat and moisture within the heap. The boundary conditions at the surface of the heap do not take rain-fall into account so the predicted final moisture content of both forest residue and SRC are much lower than observed. The inclusion of rain fall in the surface elements would be expected to raise their moisture content and lower their temperatures.

The model was used to predict element temperatures, dry matter losses and moisture content changes over the chosen monitoring period. The dry matter and moisture changes were integrated so that the effects of different stack geometry could be compared over a storage season. The convective air flow through the bulk was also reported by the model.

3.7 Spore measurements and dust monitoring

A single spore measurement exercise was carried out at the end of the trial to investigate the potential risk to workers exposed to dust thrown up when handling wood chip which has been stored for a long period of time. A teleporter machine was used to dig approximately four metres into the end of each pile to expose a vertical face that was to be used for interim sampling. The disturbance and removal of the wood chip was thought to mimic the effect of loading wood chip from a stock pile, providing the basis for the spore measurements. In addition to spore sampling, personal dust monitoring was carried out to ascertain dust levels during chip movement.

Three spore sampling points were selected, which were

- 50 metres upwind of both the forestry residue and SRC piles
- 10 metres downwind of the forestry residue pile and
- 10 metres downwind of the SRC pile

The presence of arable fields on either side of the storage prevented downwind sampling at a distance of 50metres. The precise location for the 50metre upwind sampling point was within another wood chip storage pile (independent of this particular trial). Therefore, the sampling point was positioned adjacent to this point but would not have been affected by bioaerosols from the forestry residue and SRC piles. At each sample point a range of agar plates was used to collect several spore types. The organisms selected for monitoring were thermophilic *Actinomycetes, Aspergillus fumigatus* and moulds. The use of *A fumigatus,* (a benchmark microorganism) was chosen as it allows the assessment of potential health impacts.

For the duration of the wood chip disturbance, the three people involved in the exercise wore personal dust monitors (Anderson samplers and portable pumps (18litres/min)). One person operated the teleporter and remained within the partially enclosed cab (the window in the door was open), at all times. The second person was responsible for the collection of interim samples close to the piles and the third person conducted the bioaerosol monitoring. Two static sample points were set up, which were 10metres downwind of the forestry residue pile and 20metres downwind of the SRC pile.

A weather station was used to determine the wind speed and direction. In addition temperature, humidity and cloud cover were also recorded.

3.8 Temperature measurements

An array of 12 type K thermocouples was buried within each of the piles. The layout is shown in figure 6 below and was the same in both piles. The temperature of each thermocouple was read around once per week using a digital thermometer. A min - max thermometer was also positioned at the edge of the SRC pile along with a rain gauge to measure local weather conditions. In addition weather data was obtained from the nearest met office weather station at Church Fenton.

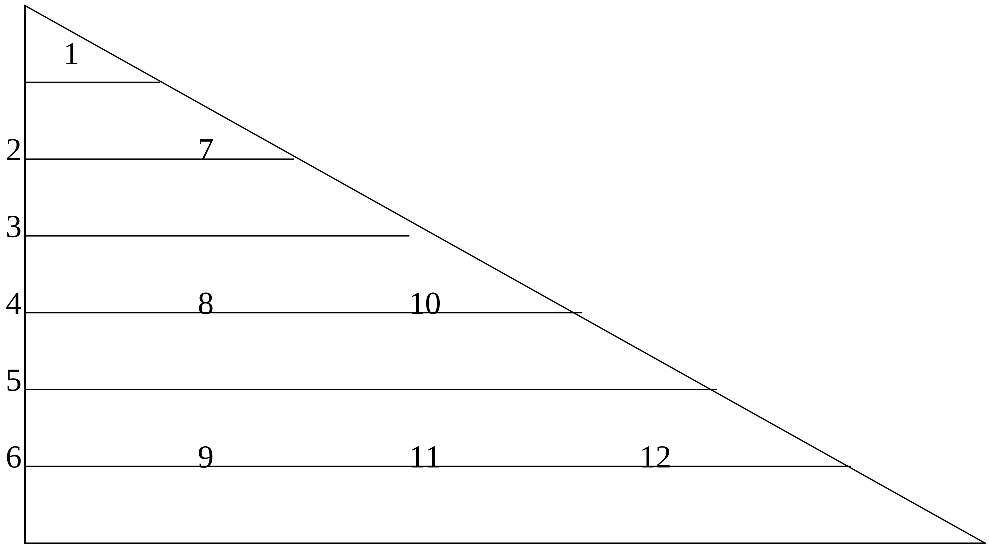


Figure 6. Location and identification number of the thermocouples positioned within the forestry residue and the SRC piles

4 RESULTS

4.1 Weather

The temperatures within the pile and its moisture content may be influenced by the ambient conditions.The daily maximum, minimum and mean temperatures, obtained from the met office weather station at Church Fenton, are shown in figure 7. The monthly rainfall over the trial period is shown in fig 8.

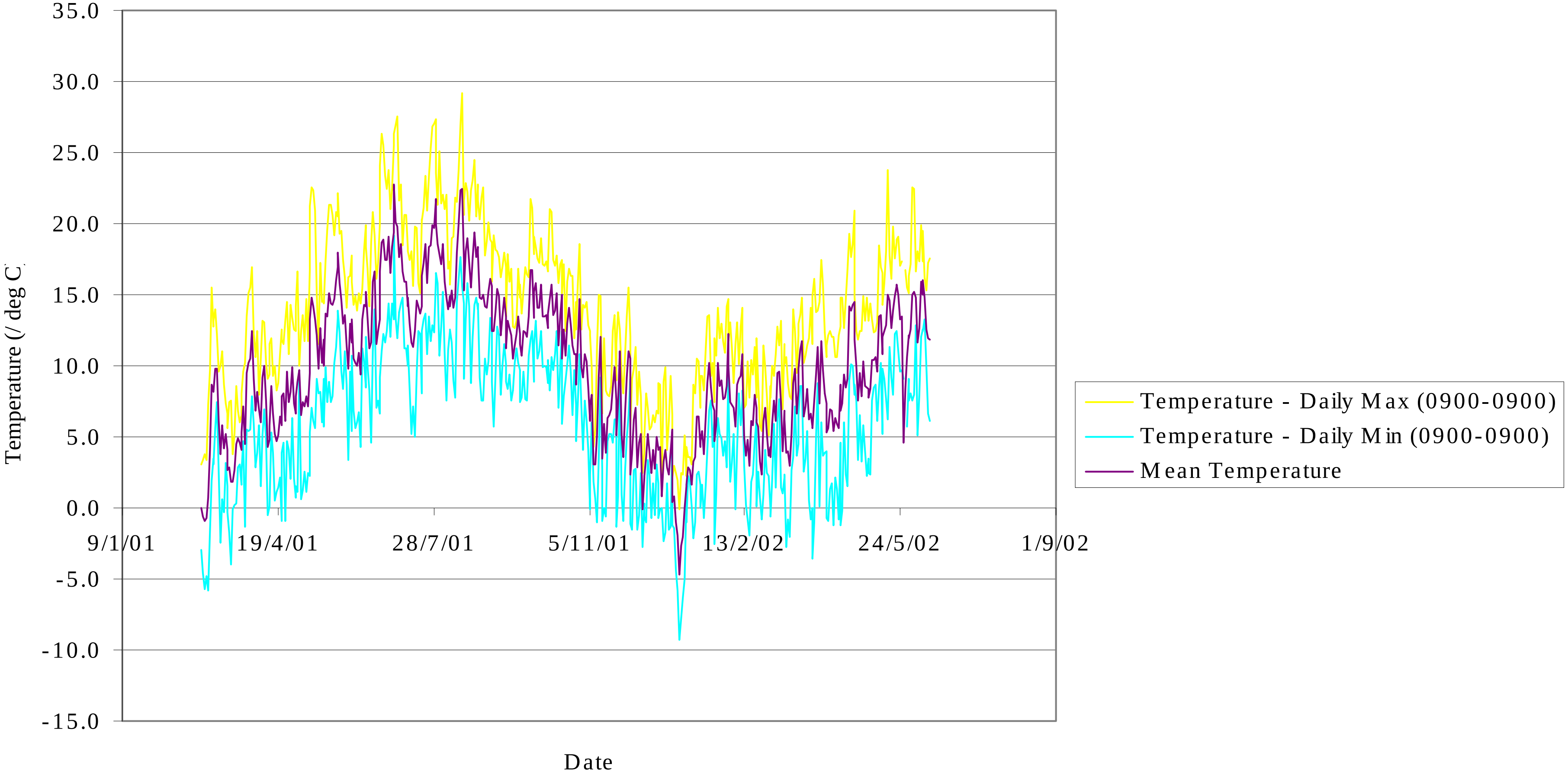


Figure 7. Daily mean maximum and minimum temperatures

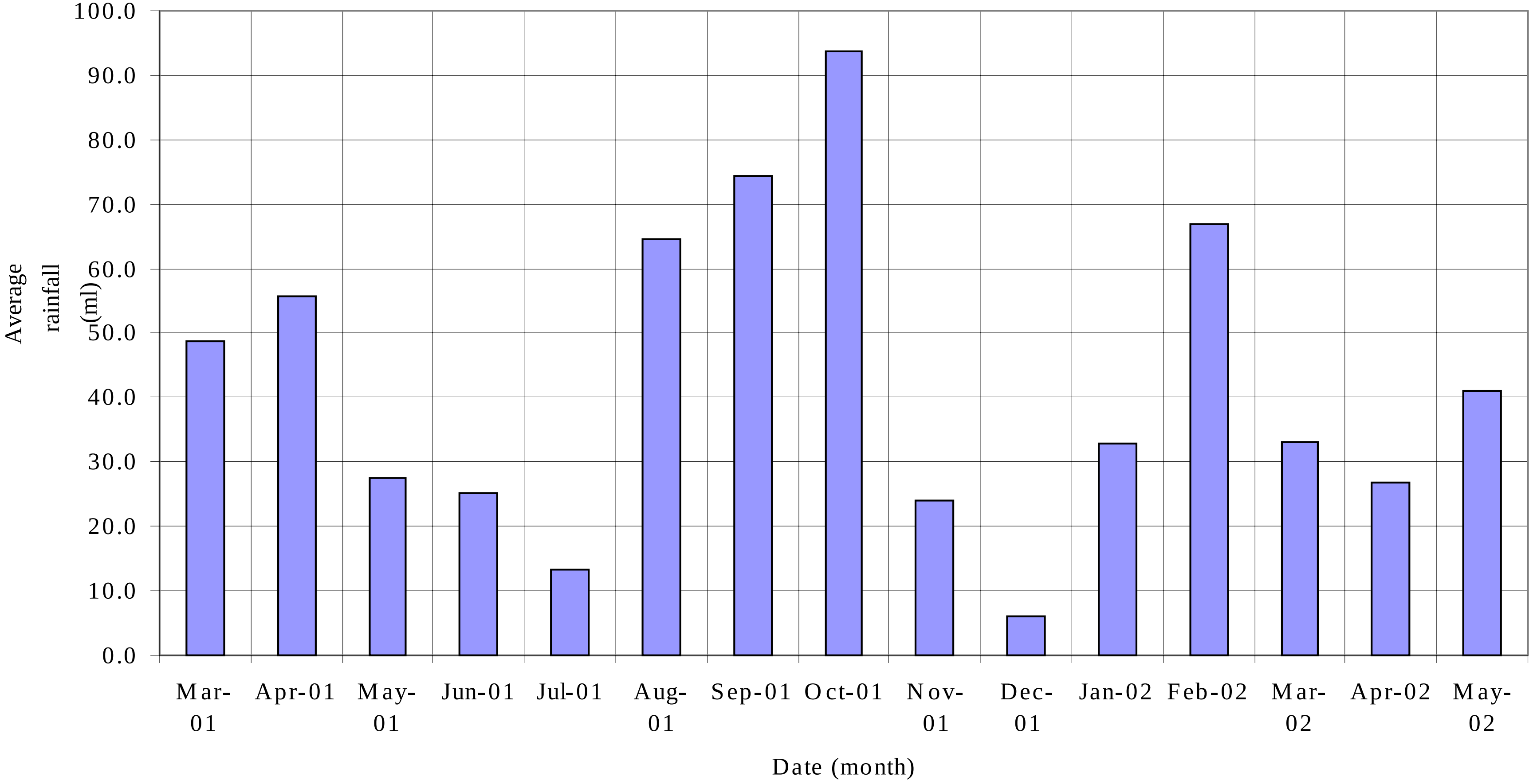


Figure 8. Average monthly rainfall (mm)

4.2 Moisture content

The following graph, figure 9, shows the percentage moisture content of the SRC wood chip at different depths throughout the period of the trial. The chip moisture content during the first 25 days in storage was erratic. Over the course of the trial the moisture content increased during the winter months and decreased during the summer months. Predictably the top layer of the pile remained the wettest throughout the storage period. At the final reading (taken in June 2002) the moisture contents at different depths within the stack ranged between 18 and 42 percent.

The moisture content recorded at different depths in the forestry residue pile against time can be seen in figure 10. At the onset of the trial the moisture content followed the same trend as the SRC pile, notably that the initial readings were erratic and an increase in moisture content was followed by a decline, which halted at 75 days after pile establishment. In general, the lower layers of the pile (between 1.5m and 3.0m) were dryer than the top layers (0.1m and 0.5m), with the middle layer (1.0m) fluctuating between the two. The deeper layers dried to a moisture content of around 30% after about 50 days and remained at around this moisture content over the remainder of the trial.

The general moisture content pattern seen in the SRC and forestry residue piles' correlates tentatively with the average monthly rainfall data shown in figure 8. For example, at the start of the trial in March to April the rainfall was relatively high (approximately 50ml) before falling to approximately 20 ml during the subsequent months May to July. This occurrence corresponds to the increase and decrease in the piles' moisture content.

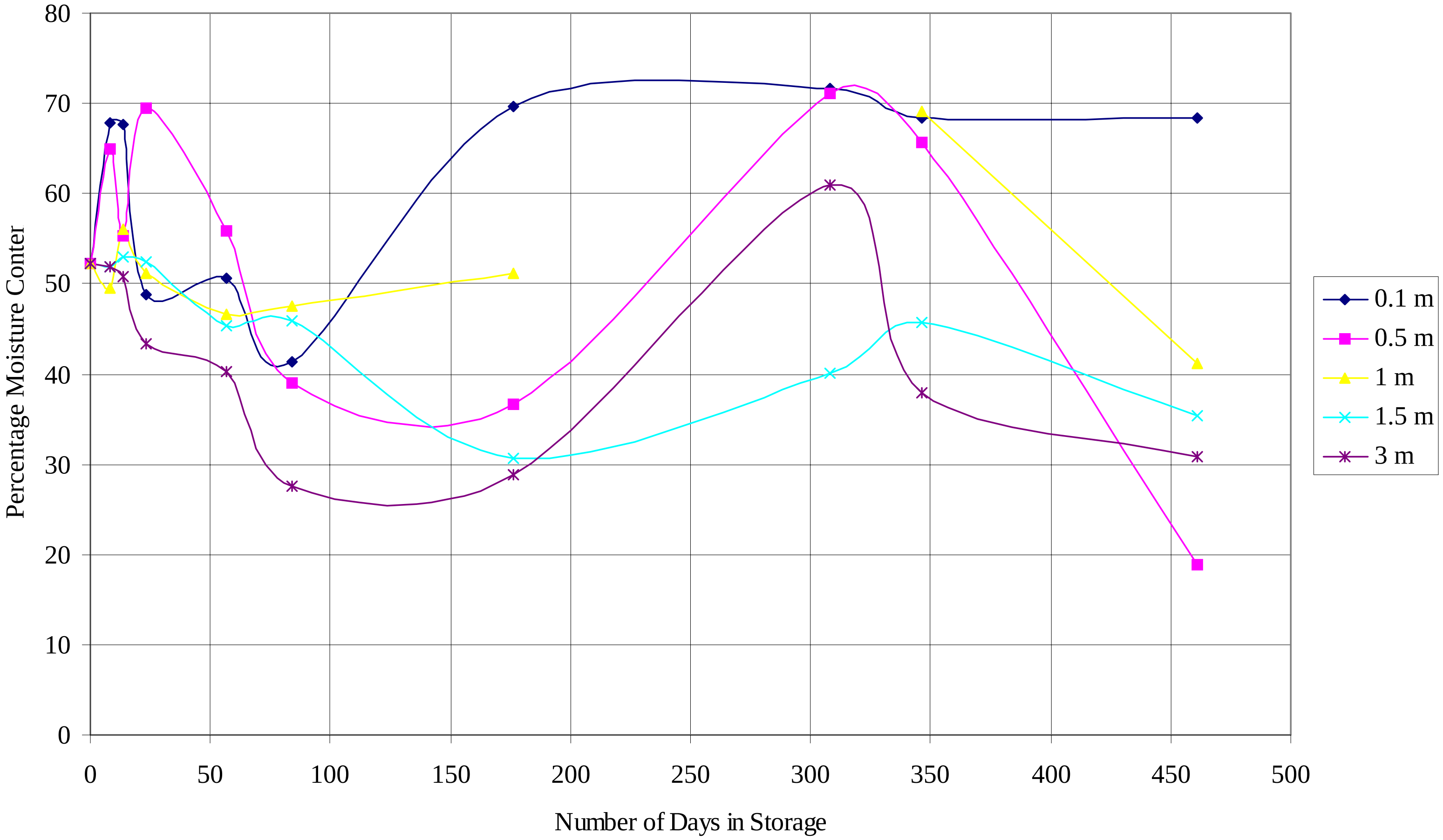


Figure 9. Percentage moisture content at different depths in the SRC pile against time

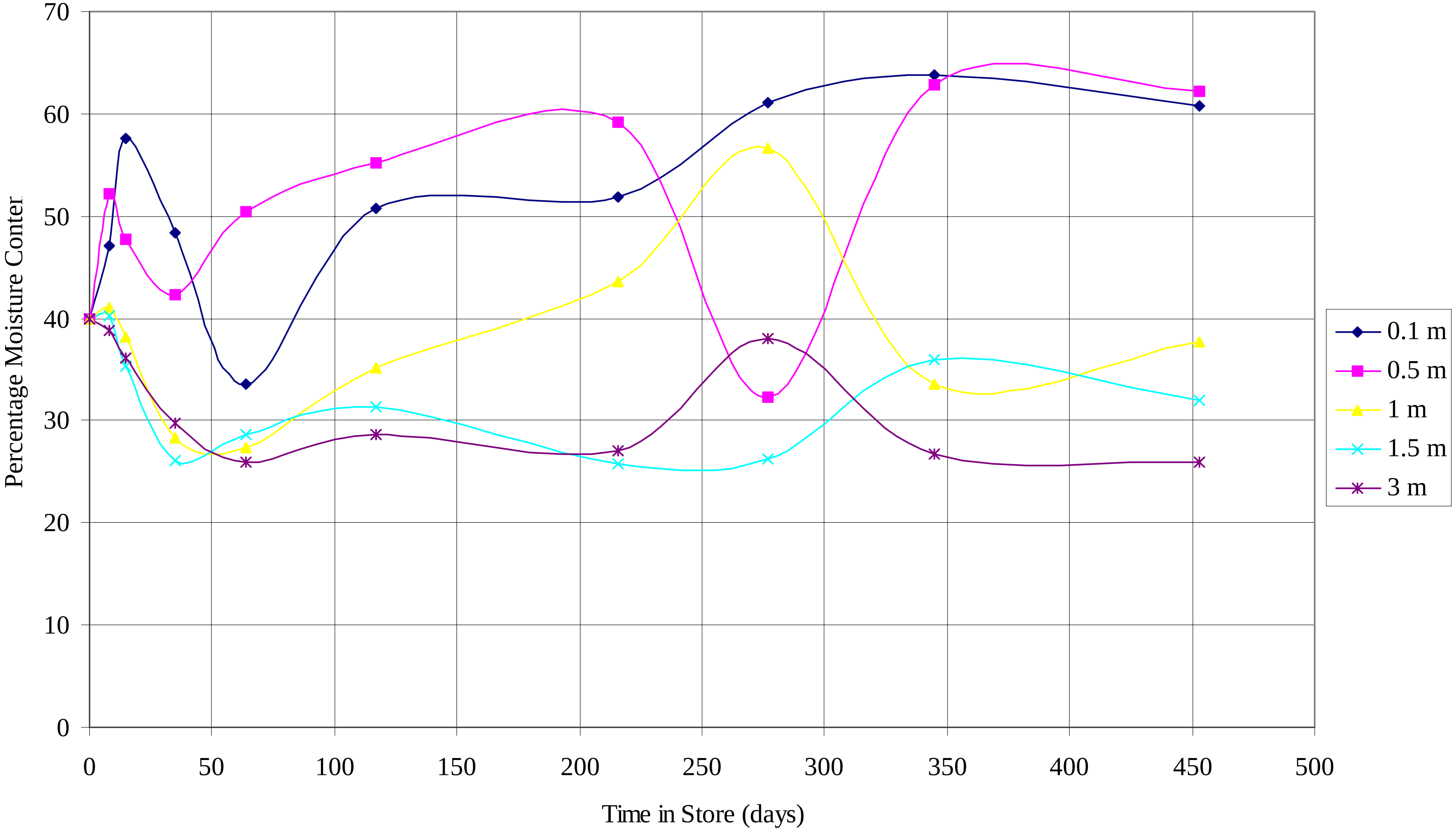


Figure 10. Percentage moisture content at different depths in the forestry residue pile against time

4.3 Ash content

The ash content of the wood chip from the SRC pile, shown in figure 11 below, showed a different pattern to that observed in the forestry residue pile. After an initial erratic fluctuation at the beginning, the ash content of the pile as a whole remained stable between 1 and 2 percent, with the exception of outlier values after 300 days in samples from 1.5 m and 3m depth.

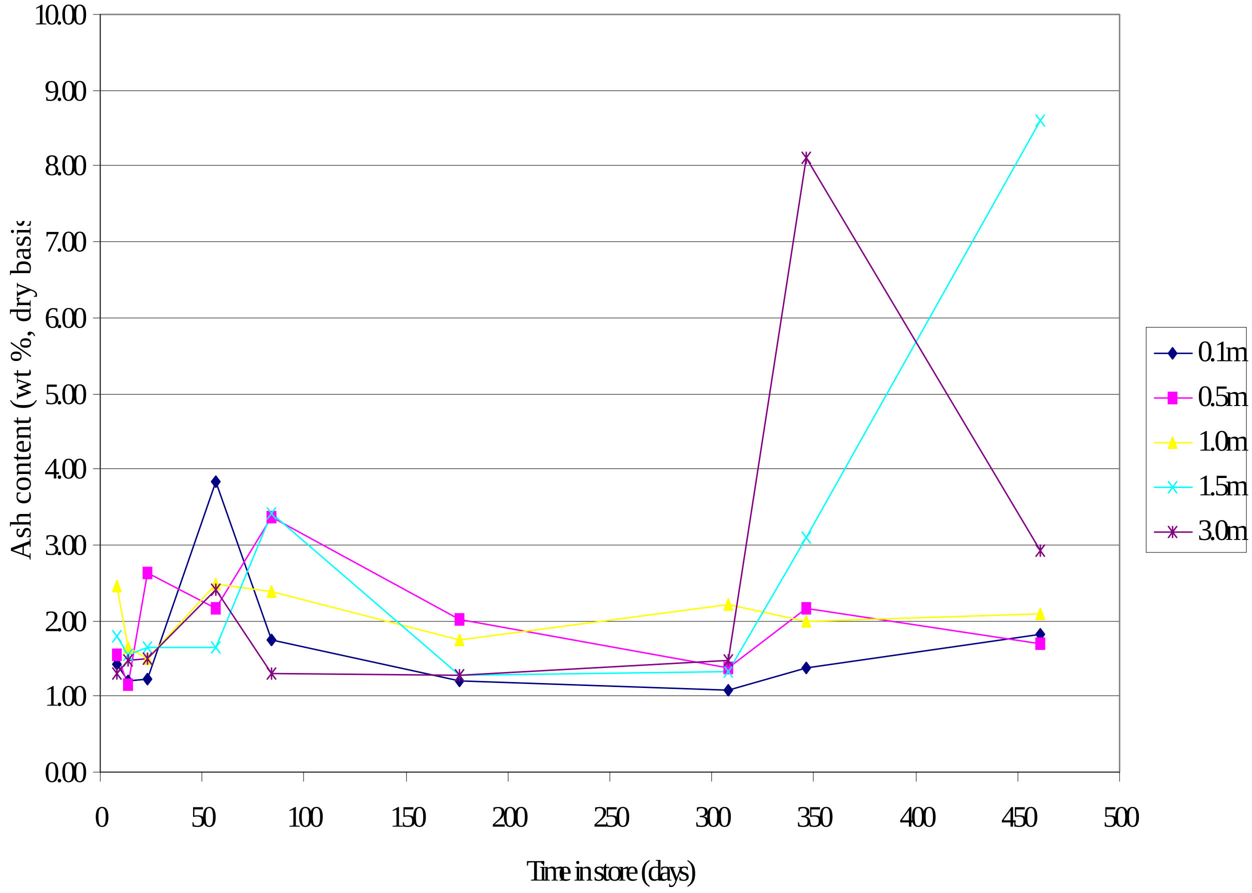


Figure 11. Ash content at different depths in the SRC pile against time

Figure 12 shows the ash content of the forestry residue wood chip at different depths against time. There were distinct variation between ash content at all the sample depths over the period of the trial, possibly reflecting the range of sources and handling of different batches. There was no correlation between depth of the wood chip and its ash content due to the wide scatter of the results.

Overall no discernible trends were found in the variation in ash content with either time or depth in either pile.

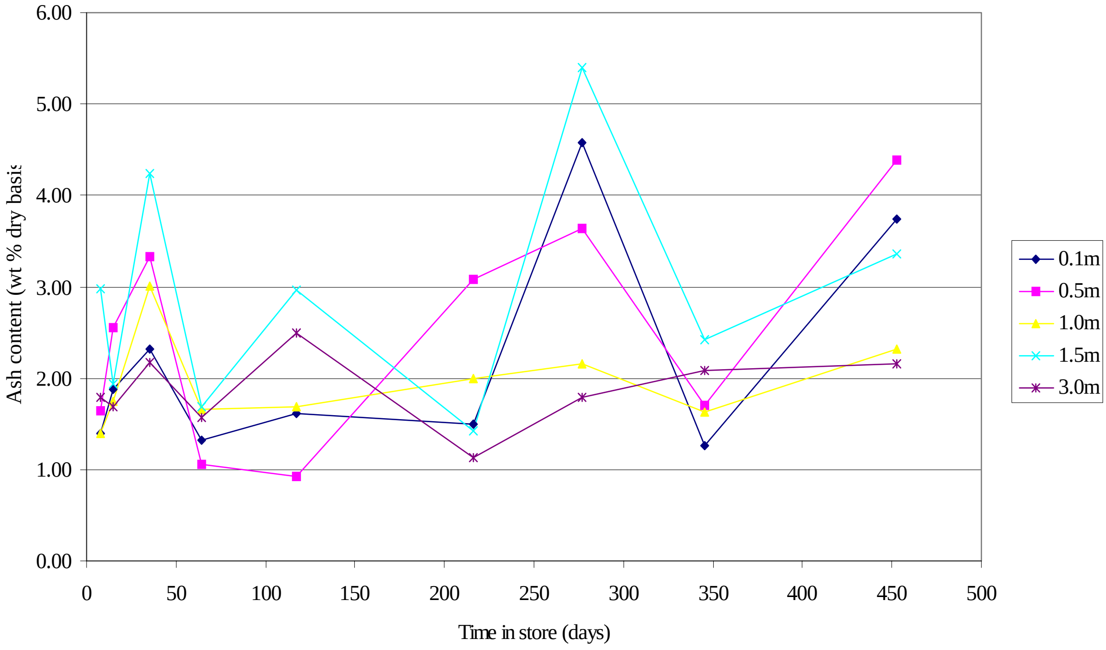


Figure 12. Ash content at different depths in the forestry residue pile against time

4.4 Calorific value

Figure 13 shows the gross calorific value (CV) of wood chip collected from various depths in the SRC pile against time. The calorific value of all of the samples collected within the first 84 days of the trial fluctuated around 8000MJ/kg. The CV of the samples collected after this date increased to approximately 13000MJ/kg before decreasing until 308 days in storage when they began to rise again back to levels recorded after 84 days. There does not appear to be a pattern correlating the calorific value of the chip with its location in the pile, except that the wetter surface layer (0.1m) CV was consistently lower than the others at the end of the storage period.

Figure 14 shows the gross calorific value of wood chip from different depths down the forestry residue pile against time. There does not seem to be a pattern in the fluctuations observed at any particular depth, but there does seem to be a relationship between CV and depth. As in the SRC, water ingress appears affect values, with the top two layers of wood chip (0.1m and 0.5m) having a predominately lower calorific value than the layers positioned towards the core of the pile.

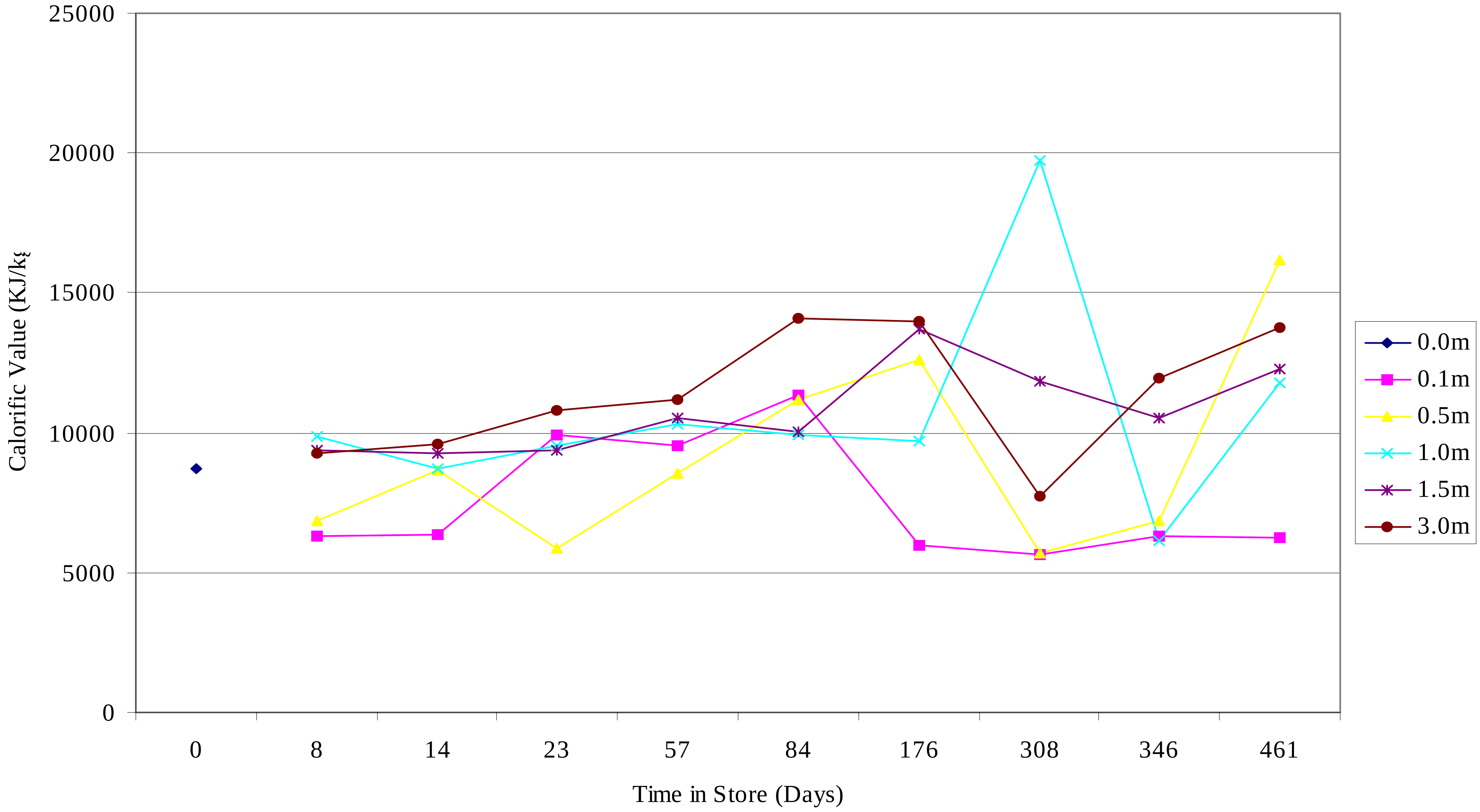


Figure 13. Gross calorific value of SRC wood chip at different depths in the pile against time

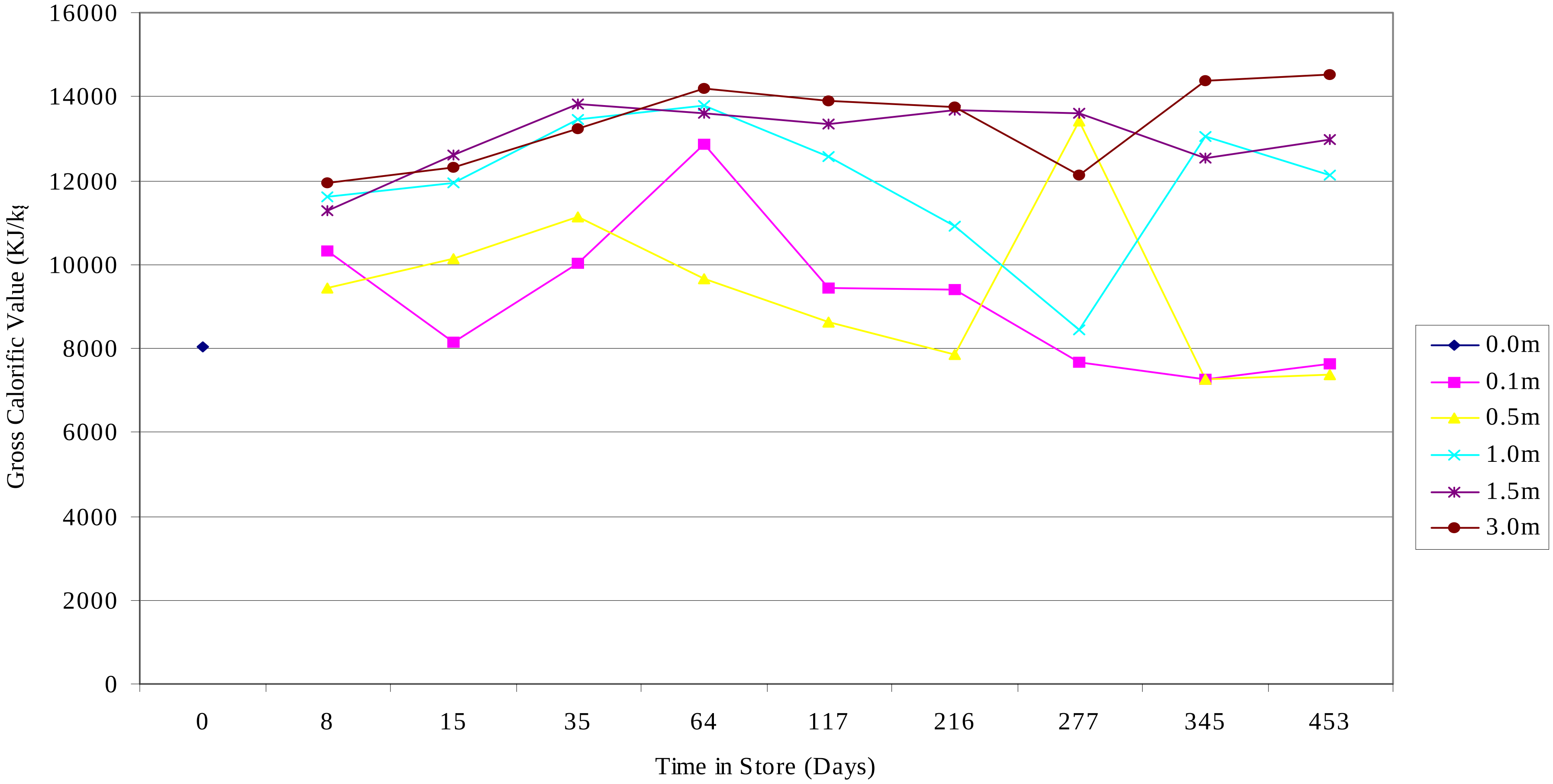


Figure 14. Gross calorific value of wood chip from different depths down the forestry residue pile against time

4.5 Temperatures

Figure 15 shows the mean pile temperature (mean of readings from all of the thermocouples in the pile) of both piles against time. It also shows the mean ambient temperature. The forestry residue pile shows a rapid rise to a peak of around 60ºC in the first week followed by a decline to around 30ºC after about 6 weeks. Going into the autumn of 2001 the temperature decreased further to a winter low of around 15ºC. In the spring of 2002 the temperature began to rise again. The SRC pile followed a similar pattern, but the temperature oscillated from 60ºC down to 25ºC then back up to 40ºC during the first six weeks in store. The ambient mean temperature shows the usual seasonal variation. In order to highlight the trend in elevated temperature resulting from biological activity, the mean ambient temperature has been subtracted from the mean pile temperature to give the difference between pile and ambient temperature. This is shown in fig 16. Removing the influence of ambient temperature shows the trends more clearly. Both piles rapidly increased to an excess temperature of 50ºC in around two weeks, then declined to an excess of around 10ºC over the following ~8 weeks. The excess temperature in the forestry pile remained at ~10ºC throughout the rest of the trial period, while the SRC pile reduced further to around 5ºC.

The behaviour of the core region of the piles compared to the surface is illustrated in figs 17 and 18. The core temperature is taken as the average of thermocouples 4, 5 and 8 and the surface temperature as the average of thermocouples 1, 7, 10 and 12 (Figure 6, p34). The trends have also been corrected for the effects of ambient temperature by subtracting the mean ambient temperature (see figures 19 and 20). The SRC pile seems to behave essentially as one thermal mass through most of the trial. However in the first few weeks the core did remain at a high temperature for longer than the surface. The surface of the forestry pile does appear to remain slightly cooler than the core throughout the trial period. As with the SRC this effect is most marked during the first few weeks of storage and during the second winter.

Figures 21 and 22 show the variation of temperature down the centre of each pile (thermocouples 1 to 6, 1 at surface and 6 deepest into the pile). In the SRC pile the individual thermocouple readings are very erratic and no clear trend in temperature variation with depth is visible. In the forestry pile the readings are slightly less erratic. The thermocouple deepest in the pile appears to have the lowest temperature for most of the time, but other than this, no trend emerges.

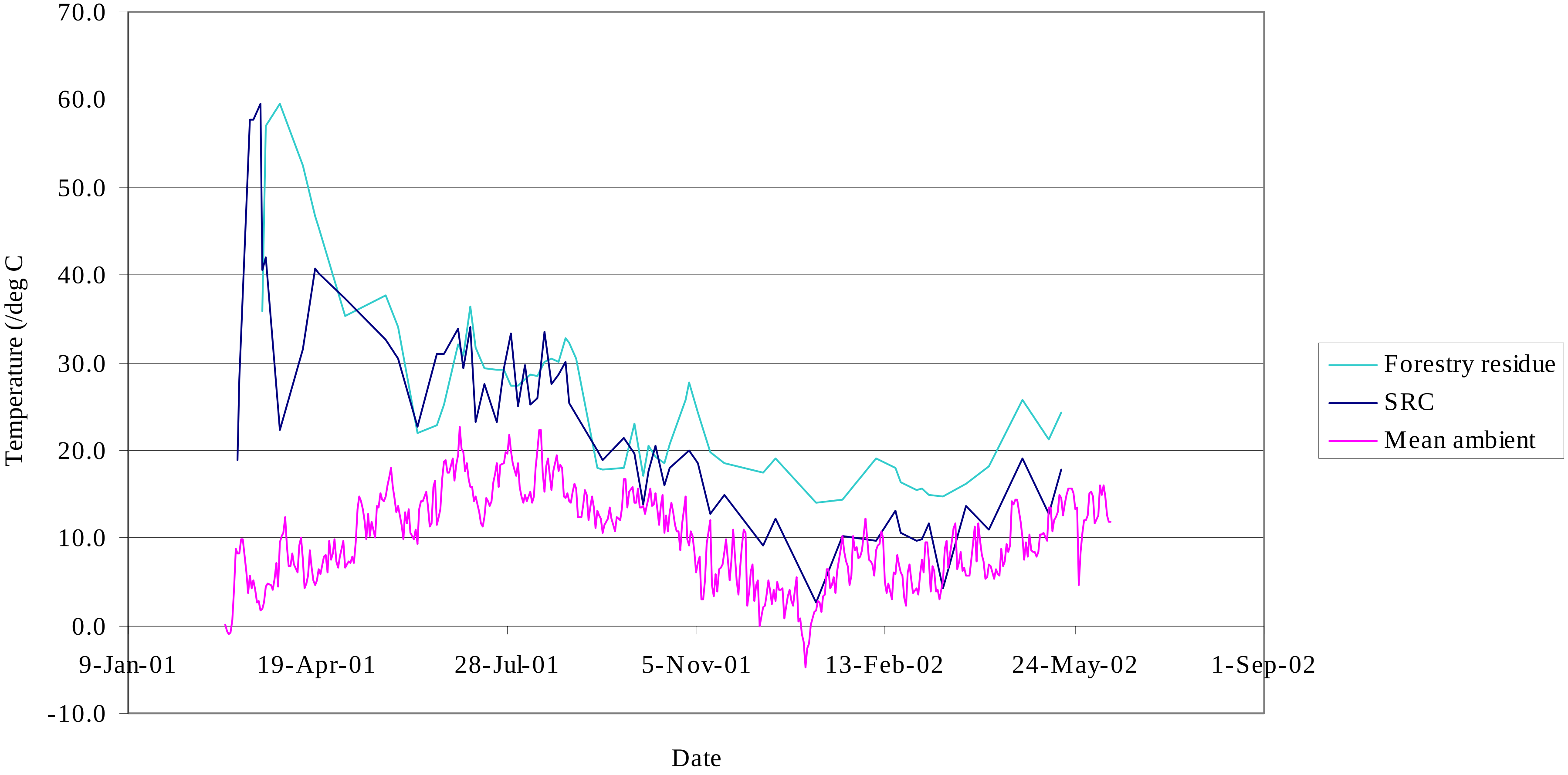


Figure 15. Mean pile temperature against time

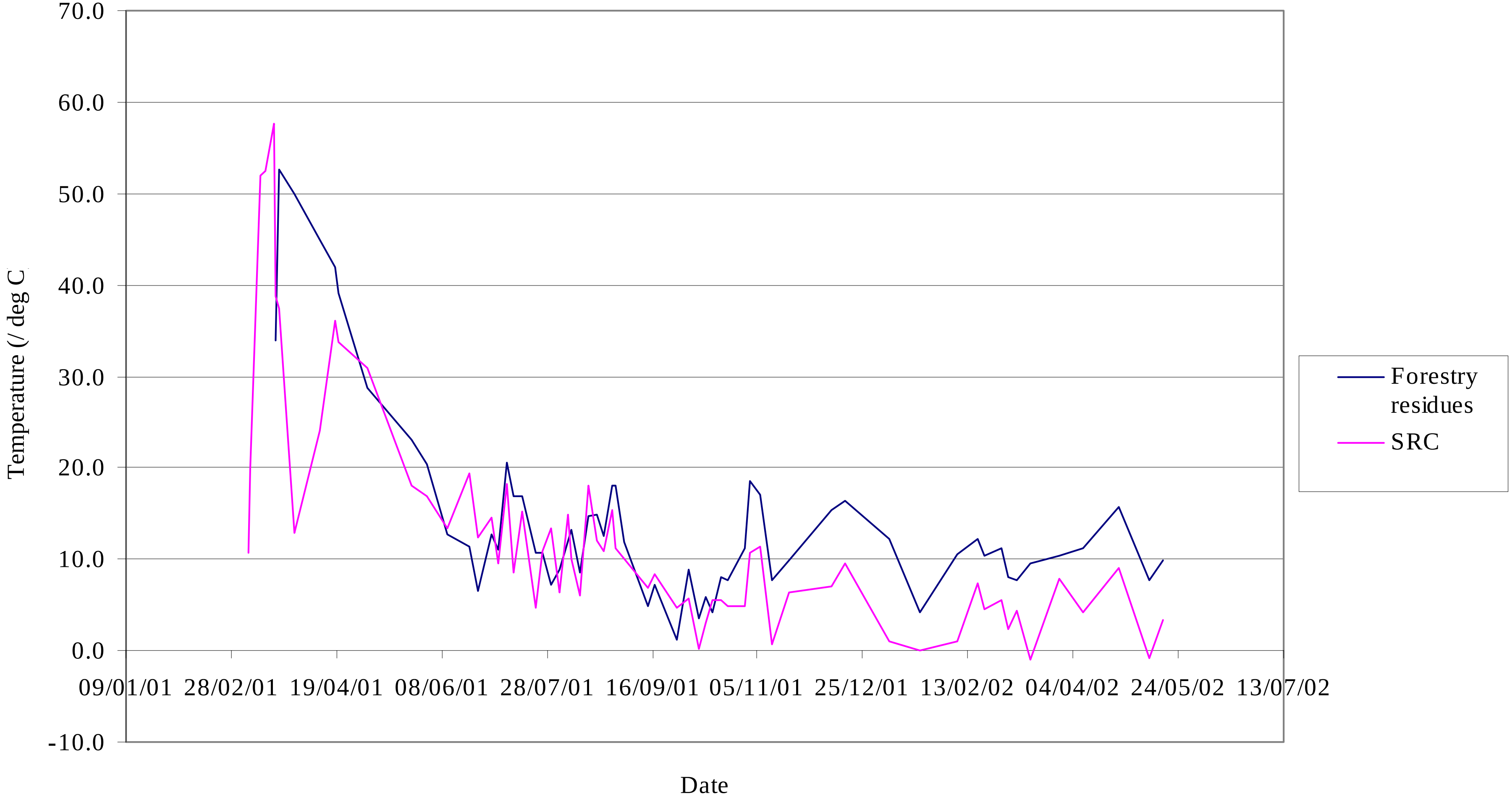


Figure 16. Difference between ambient temperature and mean pile temperature against time

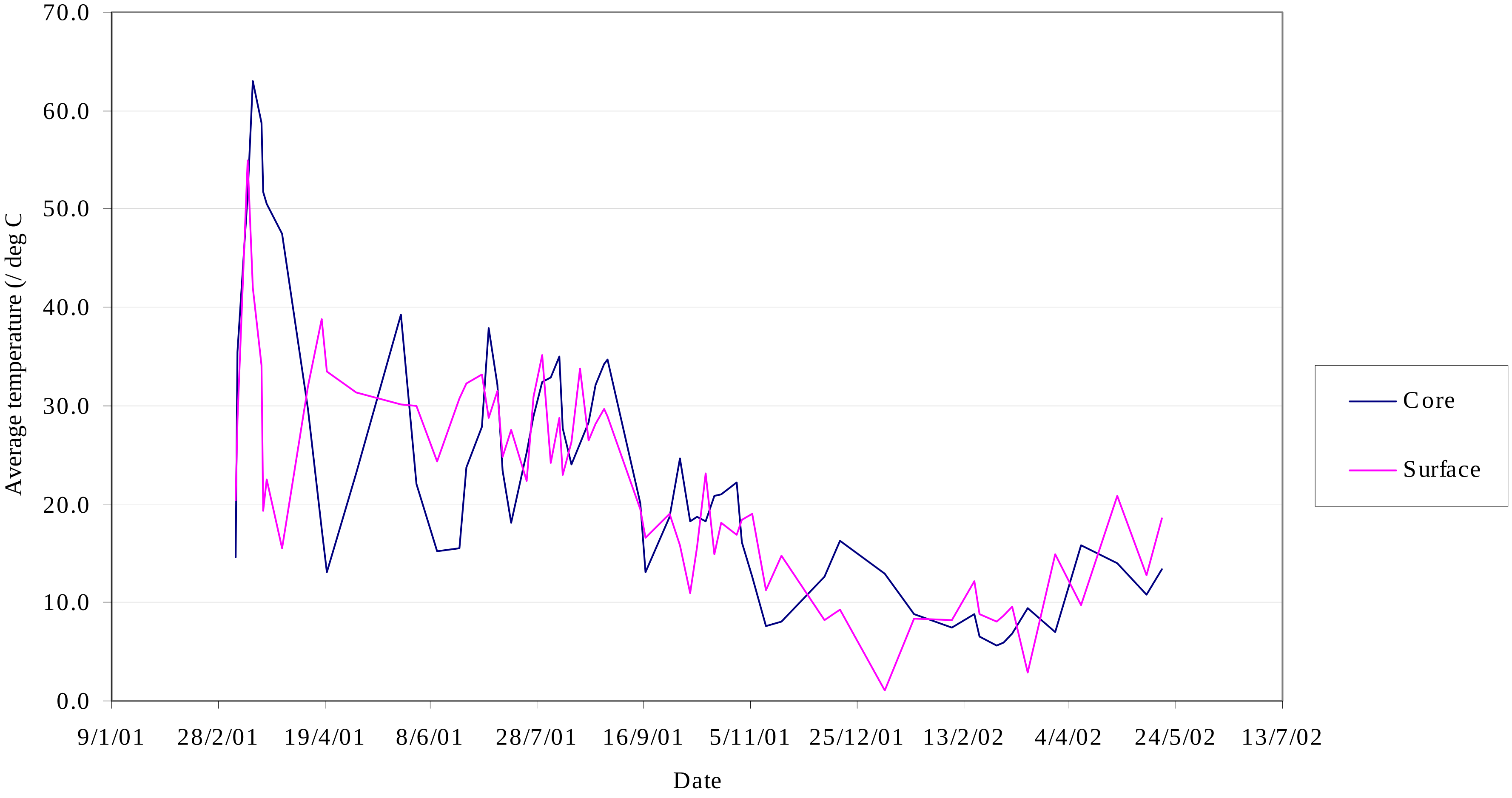


Figure 17. Average core and surface temperatures over time in the SRC pile

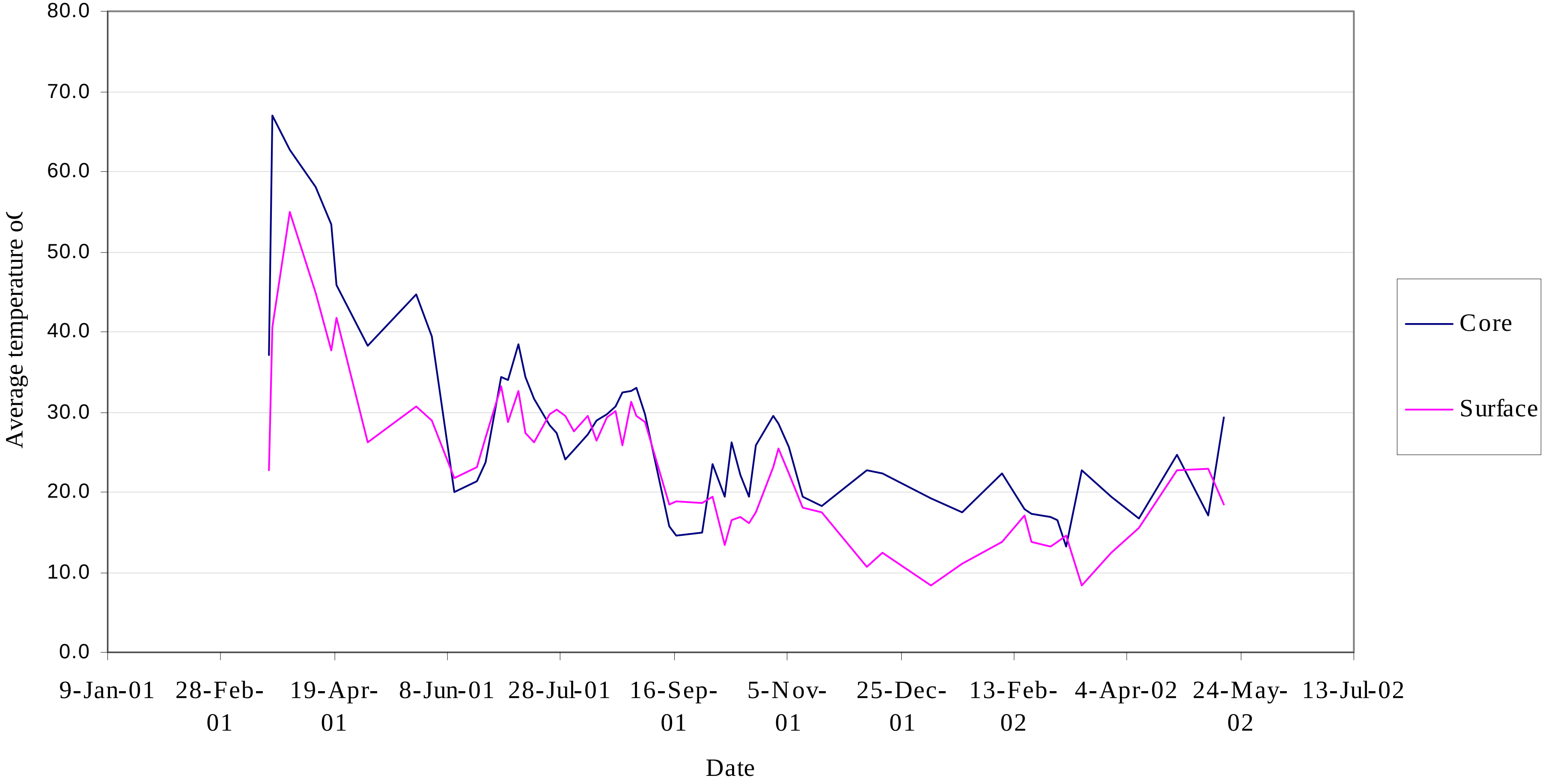


Figure 18. Average core and surface temperature against time in the FR pile

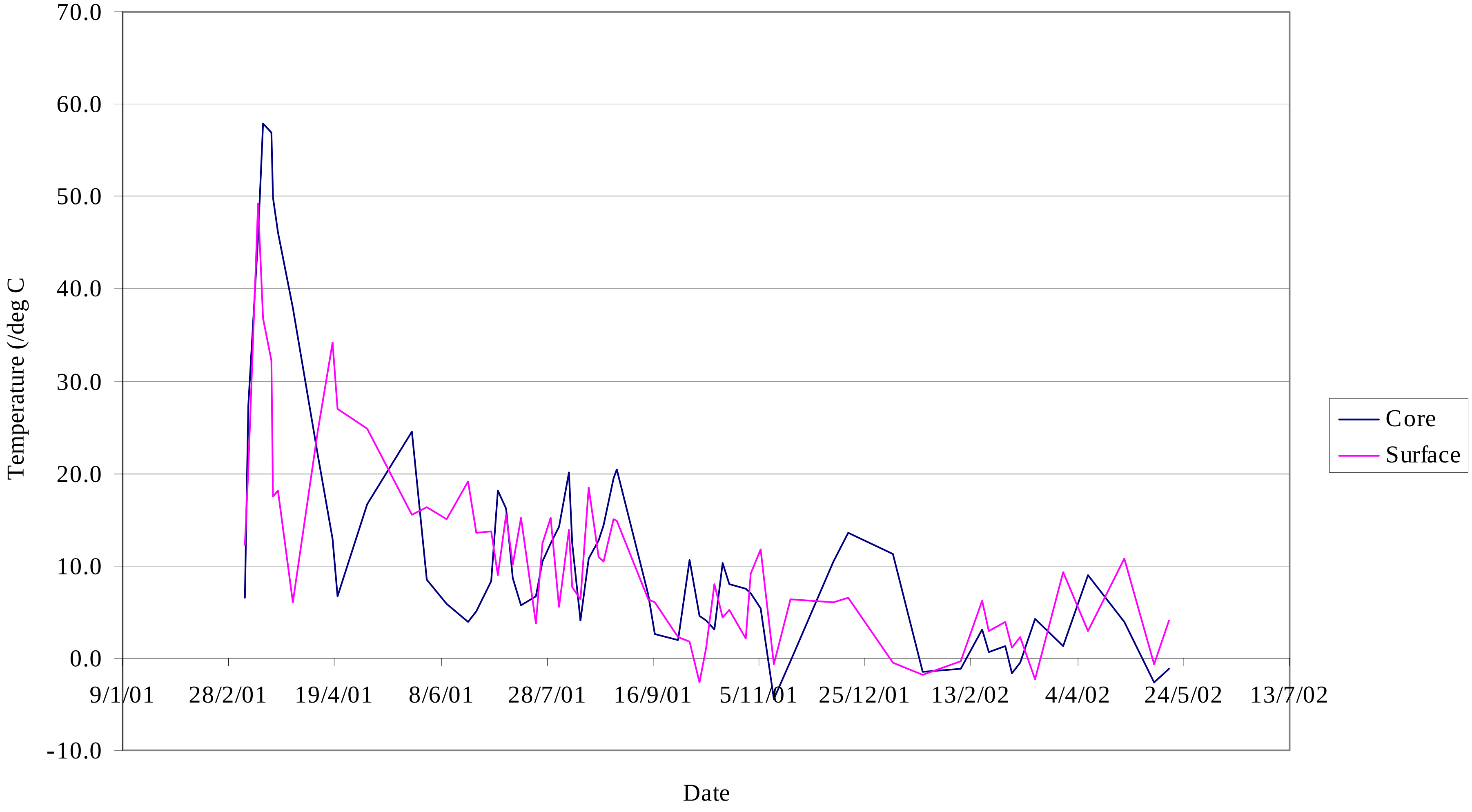


Figure 19. Difference between daily mean ambient and average core and surface temperatures in SRC pile

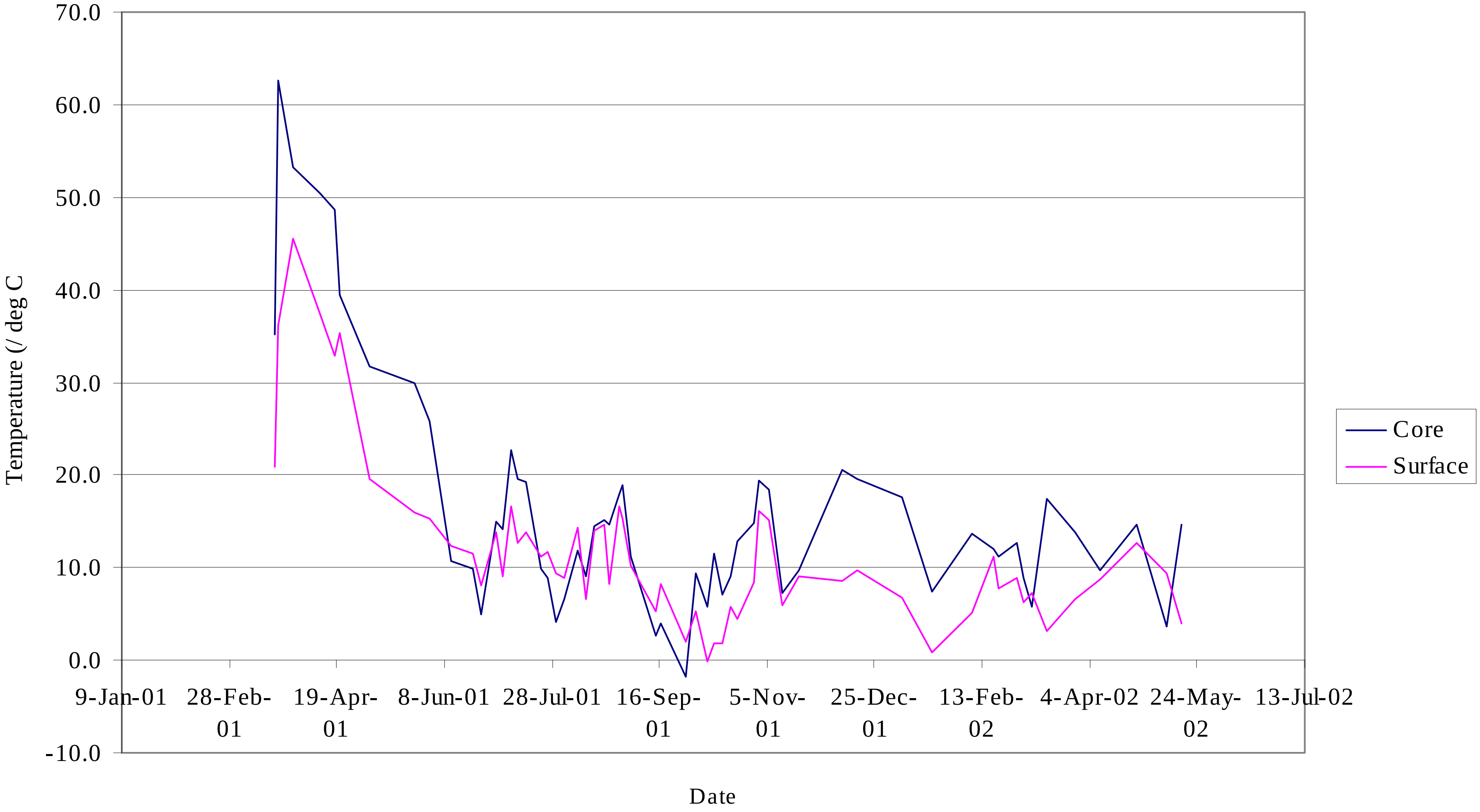


Figure 20.Difference between daily mean ambient and average core and surface temperature in forestry residue pile

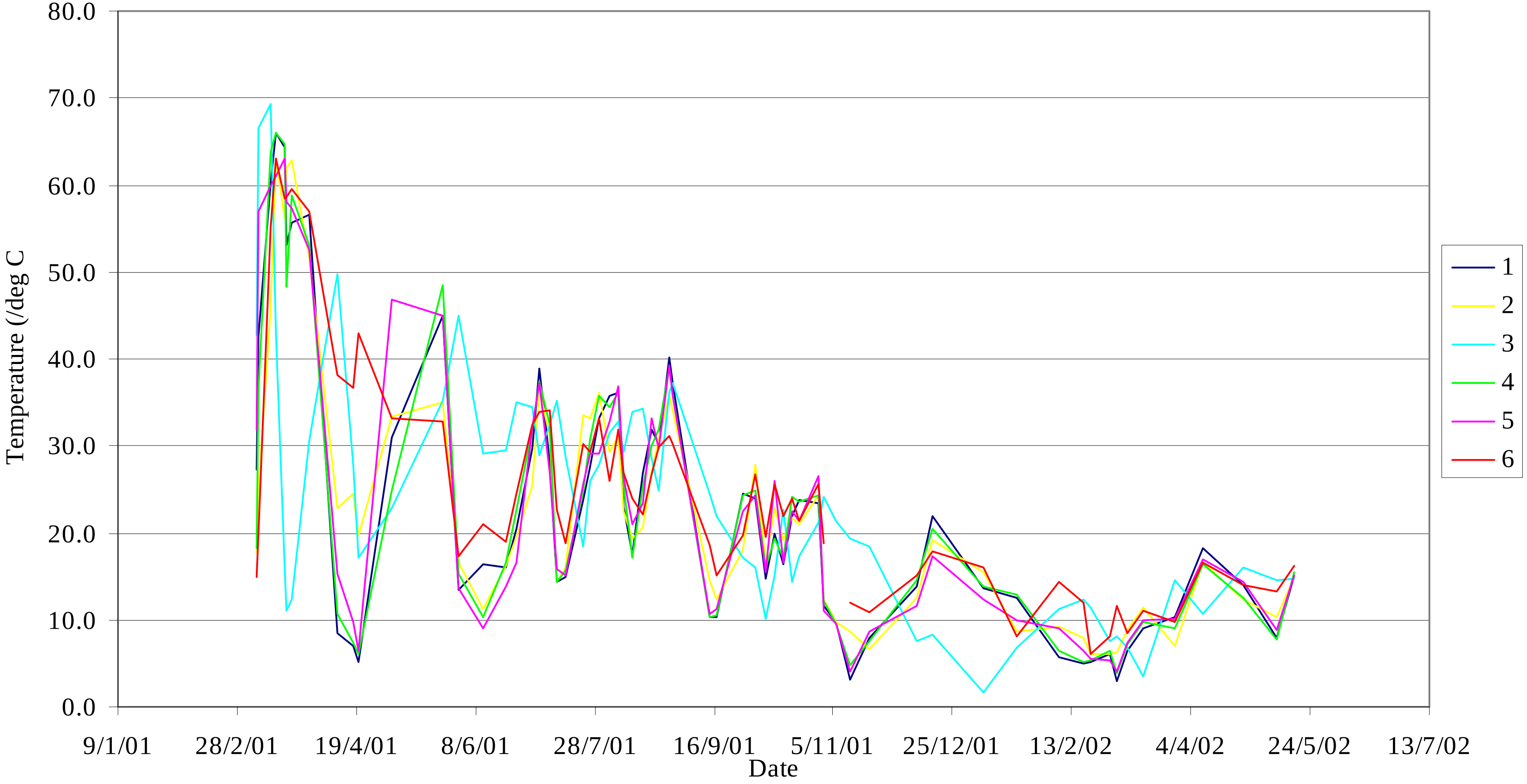


Figure 21. Temperatures along the vertical centreline of the SRC pile against time

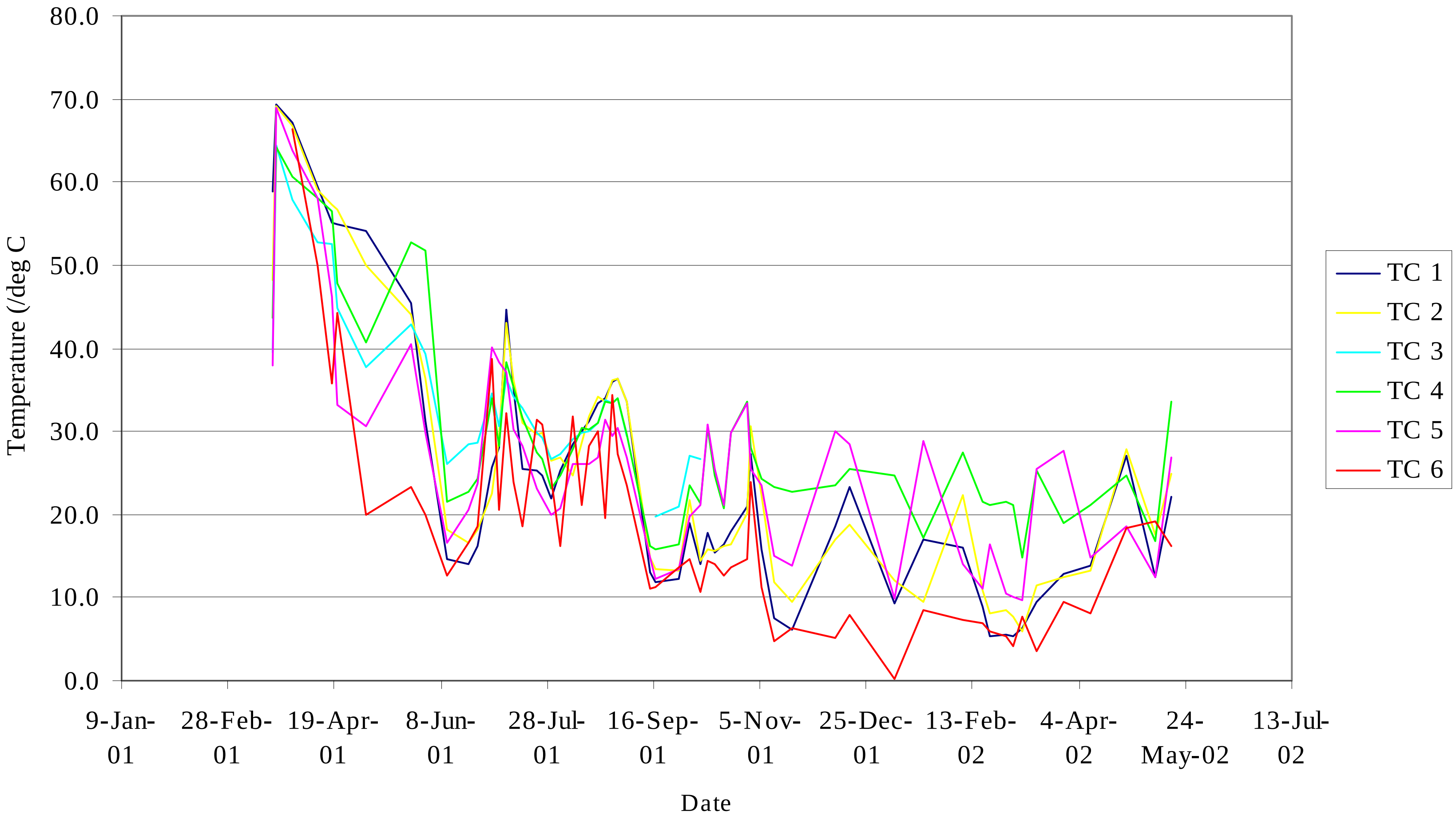


Figure 22. Temperatures measured along the vertical centre line of the forestry pile against time

4.6 Particle size distribution

Wood chip samples collected during the interim measurements were analysed for particle size distribution. The results for the wood chip taken from the SRC pile over the storage period can be seen in figure 23. The amount of fines (particles passing a 3mm sieve) in the pile does not vary from the onset to the completion of the trial; the results are variable and do not show a specific trend

The particle size distribution of the wood chip in the forestry residue pile against time (figure 24) does not show any pattern in changes in particle distribution with time.

The fraction of fines in the forestry residue pile is greater than that in the SRC pile (the global averages were 5.0% and 1.0% respectively).

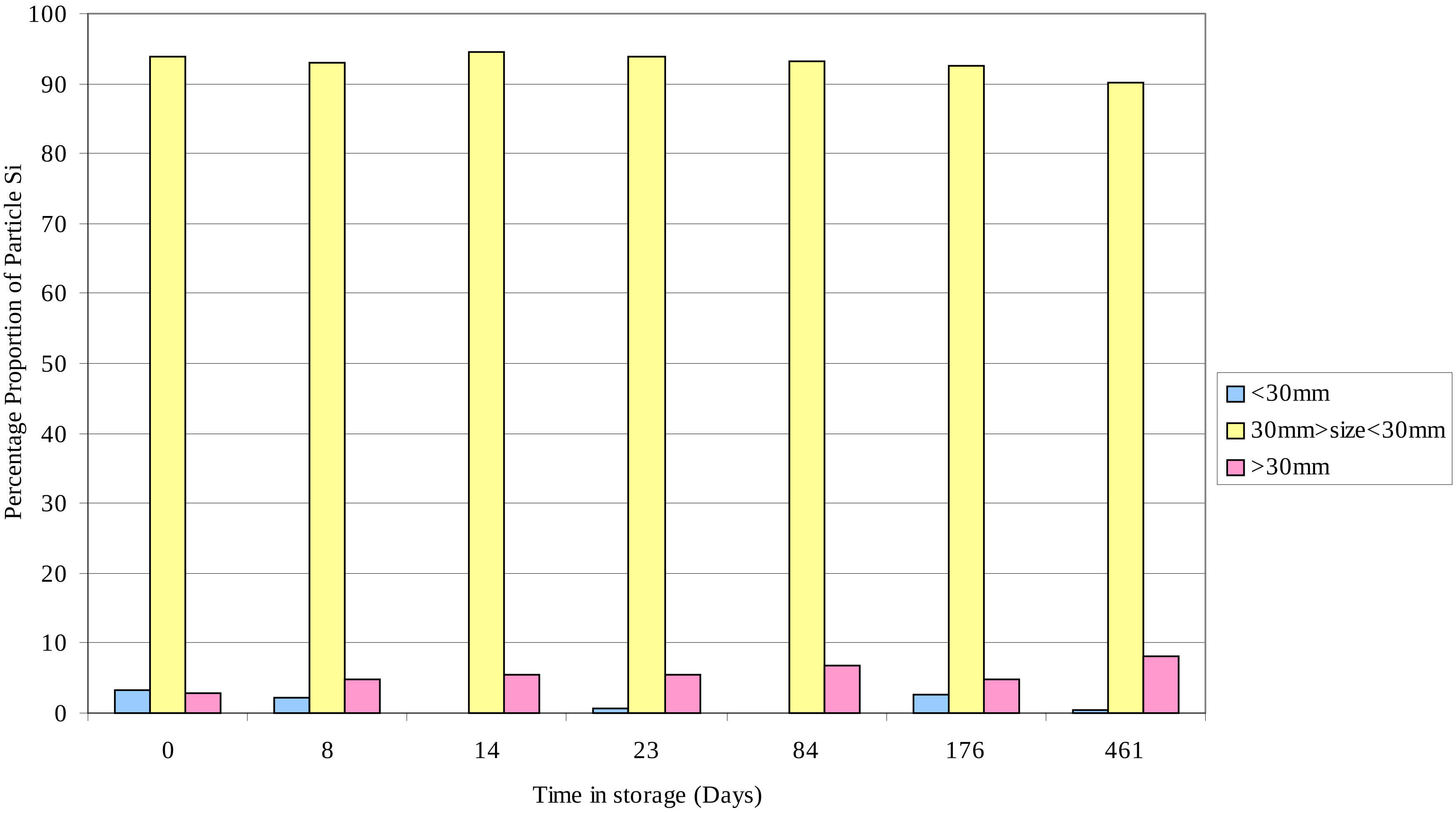


Figure 23. Particle size distribution of SRC wood chip against time

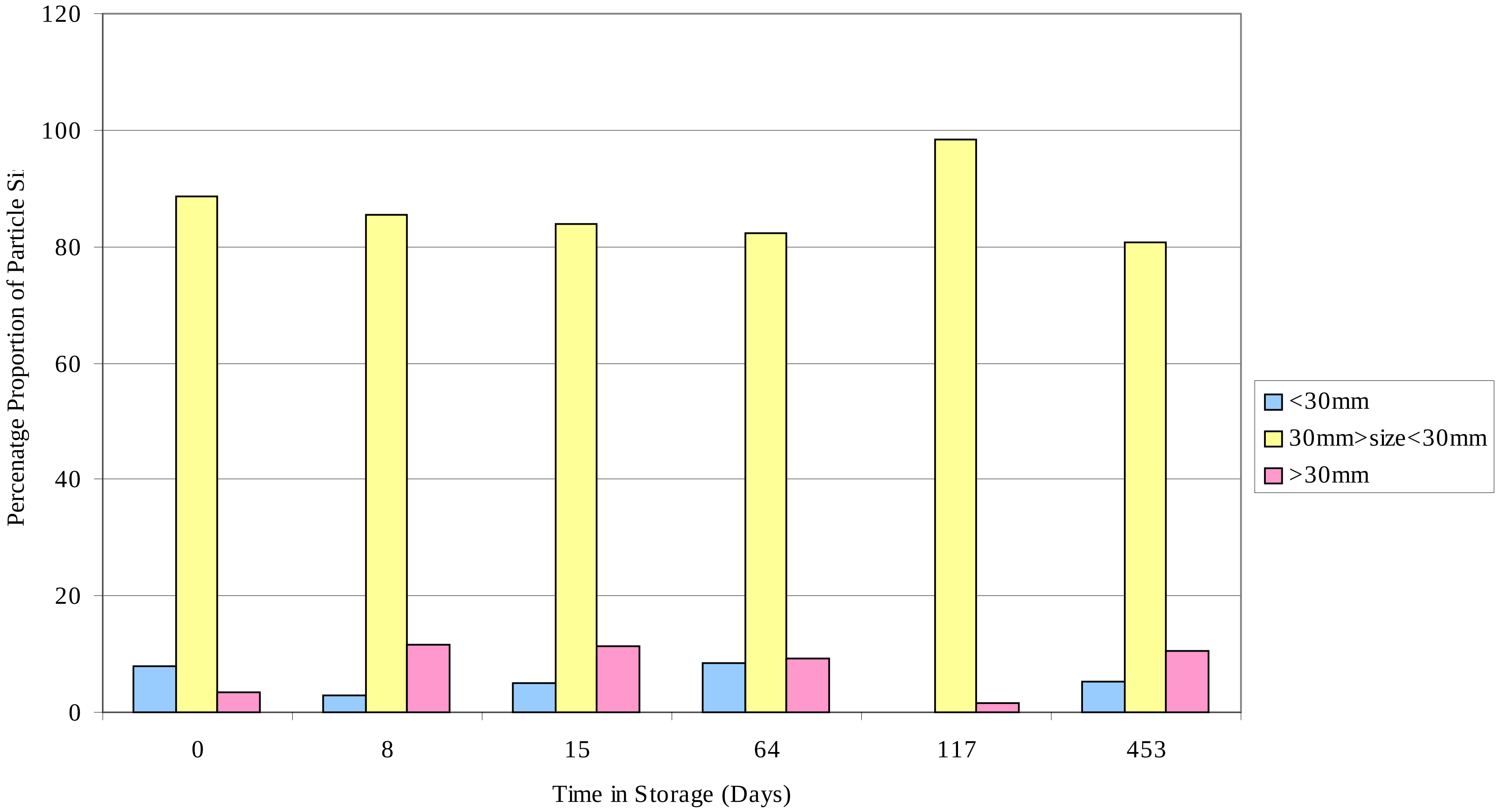


Figure 24. Particle size distribution of forestry residue wood chip against time

4.7 Biochemical Analyses

4.7.1 Water soluble carbohydrates levels

Figure 25 shows the content of water-soluble carbohydrates in wood chip samples taken from different depths in the SRC pile. After initial erratic variations, all of the layers declined to low levels. The liberation and deployment of water-soluble carbohydrates appears to be uniform throughout the pile.

Figure 26 shows the content of water-soluble carbohydrates in wood chip taken from different depths in the forestry residue pile. The content varies during the early stages of the trial and no particular pattern can be distinguished. After 50 days in storage the lower layers of the pile (1.0m downwards) behave uniformly with identical peaks and troughs. Between 75 and 225 days in storage the top layers of the pile (0.1m, 0.5m) are elevated comparative to the rest, reaching a peak of approximately 1.25%. No difference is observed between the different depths after this and levels are low.

4.7.2 Lactic acid

Figure 27 shows the lactic acid content of the wood chip at different depths in the SRC pile. After an initial fluctuation at the start of the storage period (a decrease and then an increase in two instances (0.1m and 0.5m)), beyond day 64 no further changes occurred, the level remained at <800mg/kg. For the purpose of plotting the graph, data points of <800mg/kg were assumed to be 800mg/kg.

The lactic acid content of the forestry residue pile (see figure 28) varied in pattern from the SRC pile. The lactic acid content of the core layers of the pile (1.0m, 1.5m and 3.0m) did not particularly deviate from a baseline level of 800mg/kg. After 15 and 117 days two peaks occurred, during which time the top layers had a higher lactic acid content that the base layers.

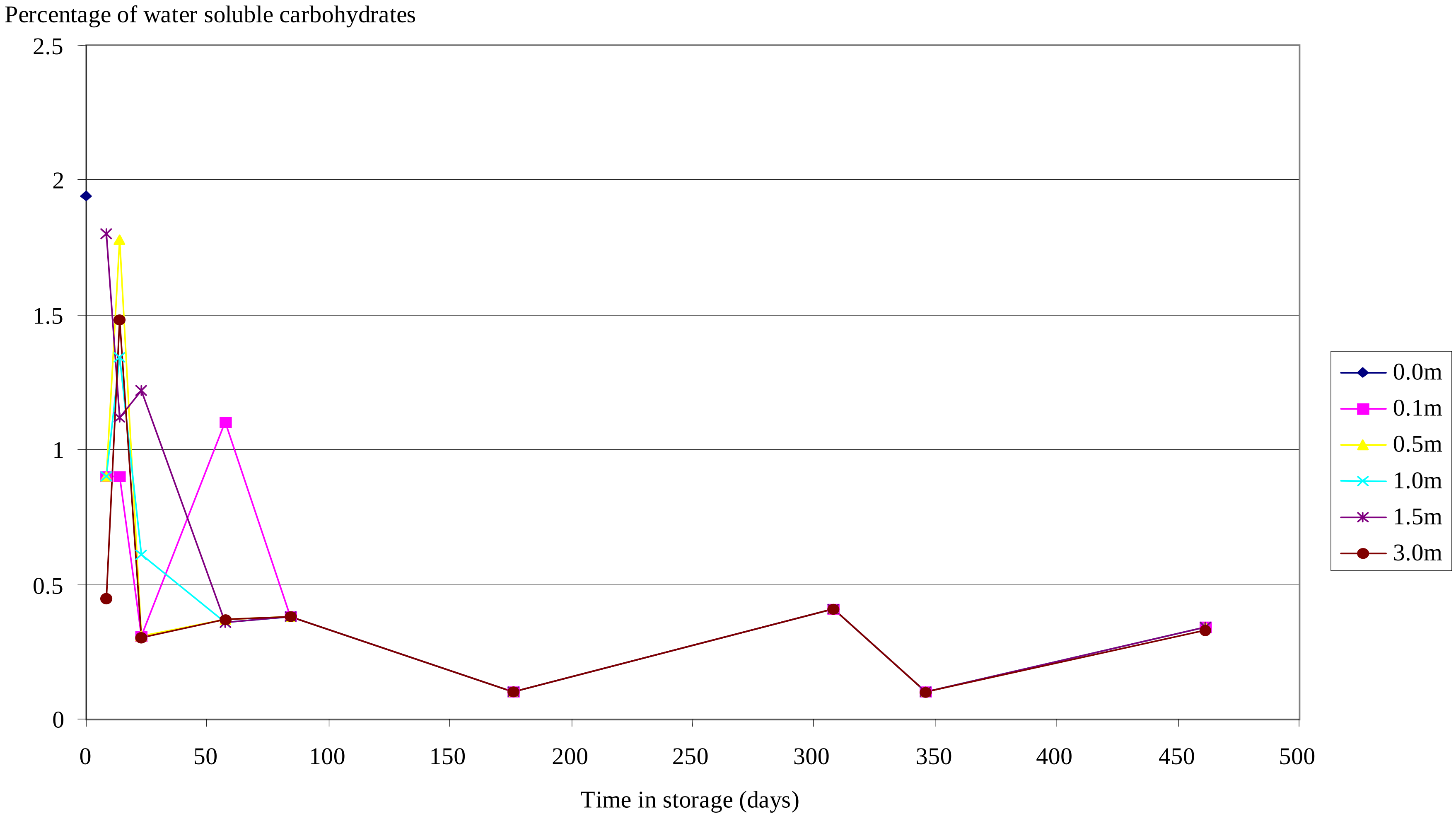


Figure 25. Percentage of water soluble carbohydrates in SRC wood chip at different depths against time

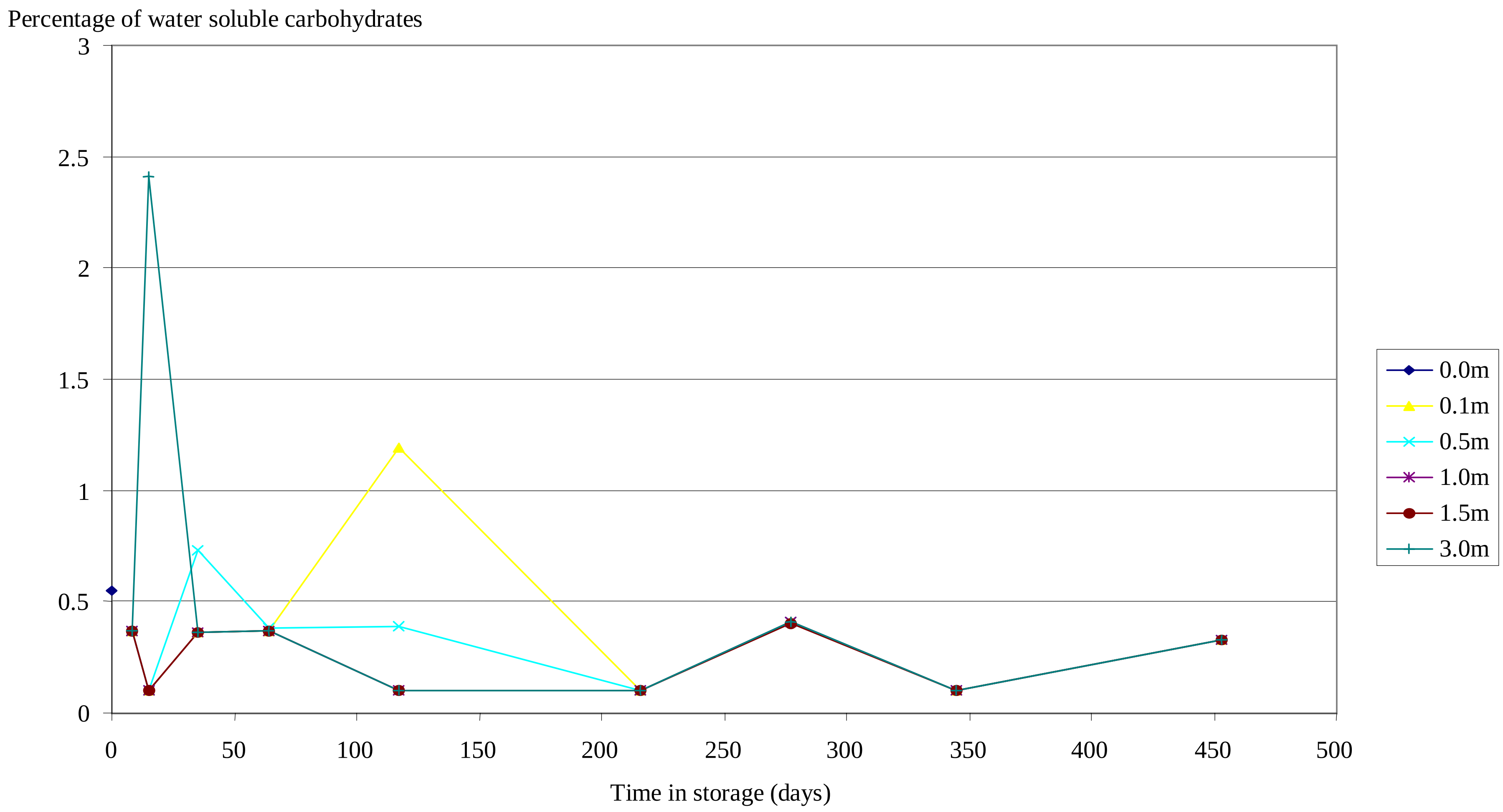


Figure 26. Percentage of water soluble carbohydrates in forestry residue wood chip at different depths against time

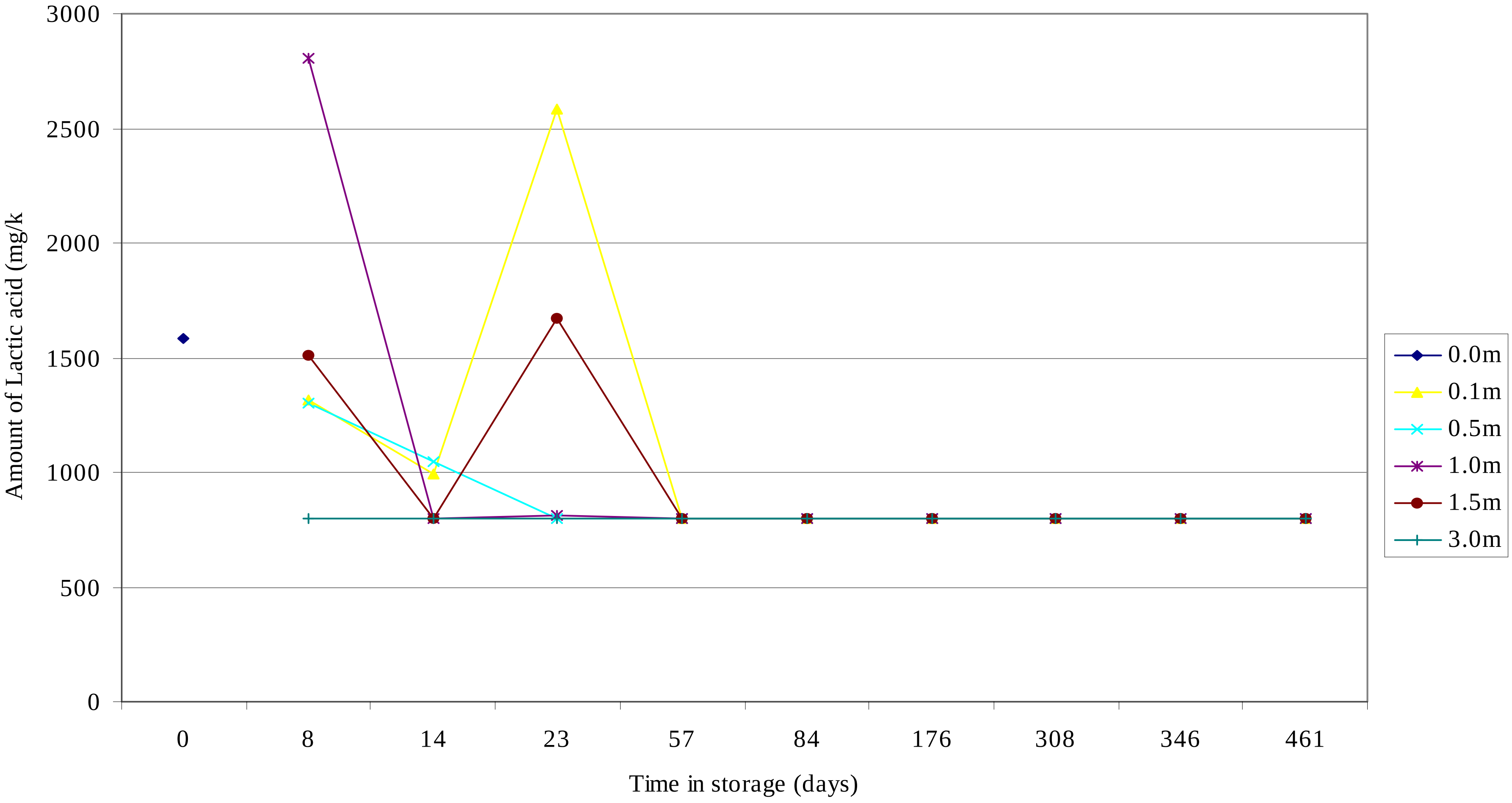


Figure 27. The lactic acid content of SRC wood chip at different depths against time

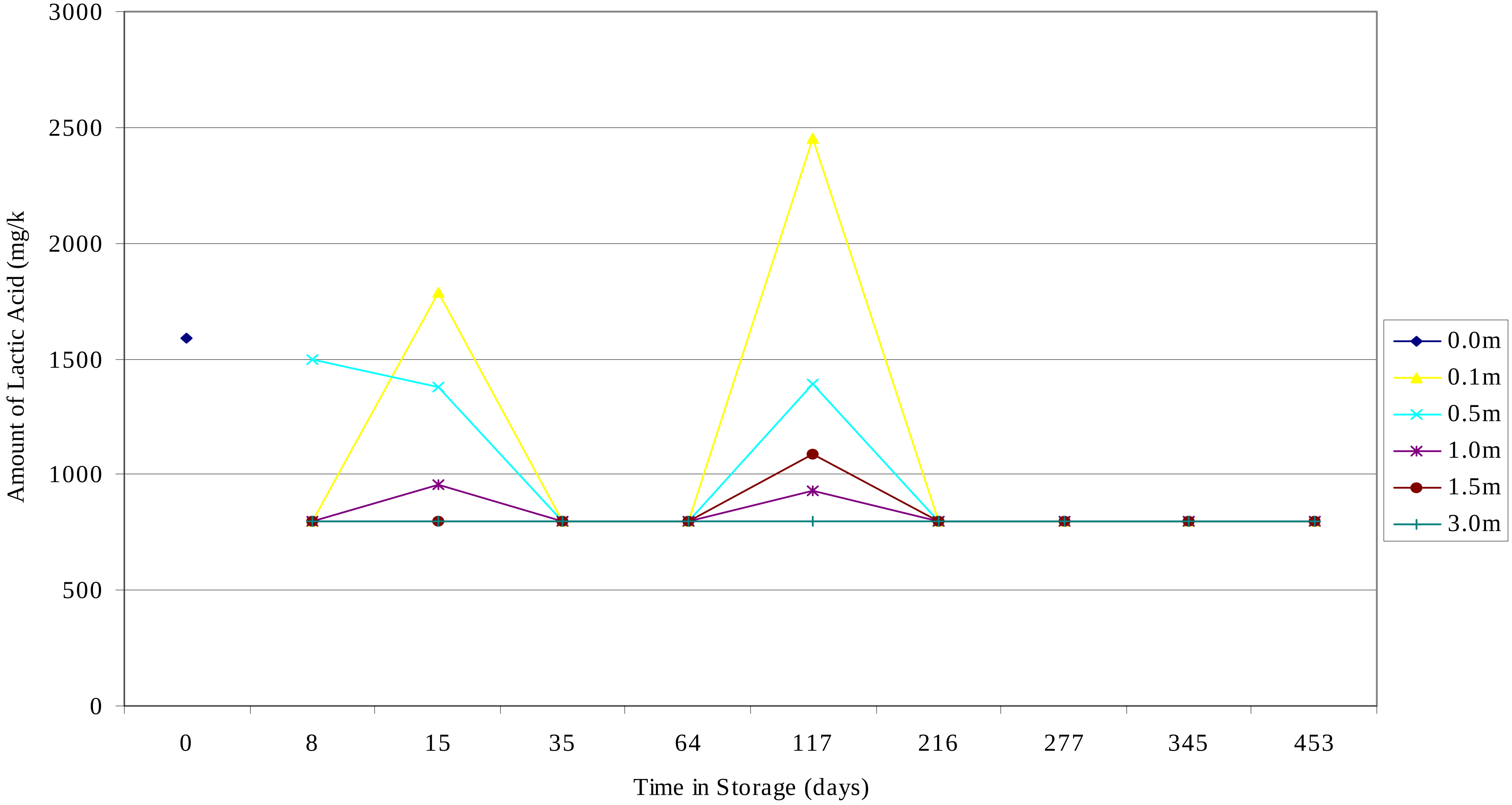
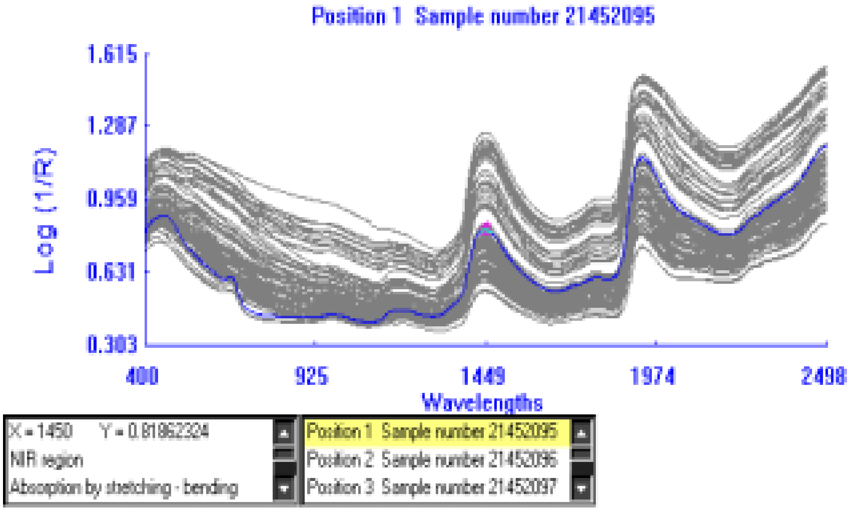


Figure 28. The lactic acid content of forestry residue wood chip at different depths against time

4.8 Near infra-red

Between March 2001 and March 2002 90 wood samples (ET001A to ET090A) were scanned and analysed by wet chemistry methods for dry matter, pH, lignin, cellulose, water soluble carbohydrates, ash, and volatile fatty acids. The samples were also presented for NIRS analysis. The data was stored in a file as log 1/Reflectance for future use (wood1.cal). The reflectance data for the 90 samples in the 400 –2500 nm spectrum are shown in the instrument plot in Figure 29.



X = 1450 Y = 0.81862324
NIR region
Absorption by stretching - bending

Position 1 Sample number 21452095
Position 2 Sample number 21452096
Position 3 Sample number 21452097

Figure 29. Log1/reflectance of 90 wood spectra

The 90 scans were then used in the winisi regression program to produce predictive equations for the previously mentioned wet analyses. Equations were generated for some of the volatile fatty acids however for the majority of these there was insufficient data to work with. For all the following calibration work the visible region of the spectra (400nm to 1099nm) was excluded so as not to influence the calibration due to sample colour (this region is mainly used in the textiles and paint industry for colour matching).

The regression program used derivative math treatments on the spectra in order achieve a better correlation with the wet chemistry, as the raw spectra contains scatter information as well as chemical information. There is no best math treatment for every application so finding this is a matter of trial and error. The tables shows the equation statistics for the best math treatment in each case. Table t gives the data for the discriminant analysis for the qualitative discrimination between FR and SCR

Constituent	**N**	**Mean**	**Est Max**	**SEC**	**RSQ**	**SECV**	**1-VR**
ODM	78	56.2910	98.1984	0.2654	0.9996	0.6804	0.9976
pH	83	5.8735	8.1033	0.2207	0.9118	0.5301	0.4893
Ligas	75	5.7021	13.3614	1.1456	0.7987	1.5320	0.6415
Cellas	81	35.2569	63.9347	2.3087	0.9417	2.8398	0.9137
Wscas	44	0.2663	0.5859	0.0372	0.8780	0.0959	0.1825
ashas	78	1.2149	3.1343	0.2758	0.8142	0.3750	0.6530

Table 5. Prediction equation for wet analyses.

The above equation shows good correlations, all of factor 0.8 and above. As the calibration file that this was generated from contained samples from two sources i.e. forestry residues (FR) and short rotation coppice (SRC), a recalibration was attempted with the two types separated into two CAL files FR.CAL and SRC.CAL. Tables 6 and 7 below shows the resulting equations.

Constituent	N	Mean	Est Max	SEC	RSQ	SECV	1-VR
ODM	38	64.5868	92.8631	0.361	0.9985	0.7203	0.9942
pH	37	6.0054	8.6924	0.5863	0.5715	0.6278	0.5241
Ligas	36	6.8469	14.6238	2.0680	0.3636	2.2520	0.2586
Cellas	34	41.6781	58.8037	3.6311	0.5954	3.8531	0.5784
WSC	19	0.2477	0.3505	0.0183	0.7150	0.0198	0.6834
Ashas	37	1.4682	3.4524	0.02437	0.8643	0.3172	0.7728

Table 6. Prediction equation for FR samples only.

Constituent	N	Mean	Est Max	SEC	RSQ	SECV	1-VR
ODM	39	48.8308	87.7075	87.7075	0.9983	0.9272	0.9949
PH	35	5.7171	7.0177	7.0177	0.2026	0.4746	0.1481
Ligas	35	5.4221	14.7106	14.7106	0.0740	3.0654	0.0333
Cellas	40	31.6463	58.3773	58.3773	0.9455	2.5290	0.9197
WSC	29	0.4280	1.2652	1.2652	0.9622	0.2293	0.3917
Ashas	39	1.0831	3.2831	3.2831	0.8145	0.3940	0.7141

Table 7. Prediction equation for SRC samples only.

It can be seen from tables 6 and 7 that there is no benefit from separating the samples into individual calibration sets at this point. This could change as the calibration set becomes larger. Prediction equations were also generated from the ADAS NIR scans and data provided by Innogy. Table 8 overleaf shows the best equation.

Constituent	N	Mean	Est Max	SEC	RSQ	SECV	1-VR
ODM	40	32.6250	113.0853	6.6133	0.9392	7.5325	0.9194
pH	40	19697.8750	20585.3730	259.9728	0.2277	281.5074	0.1085
Ligas	36	10167.7227	14198.9355	626.9125	0.7823	658.4465	0.7585
Cellas	45	1.2200	4.2745	0.7883	0.4005	0.8679	0.2654
WSC	38	47.1737	68.7256	3.5829	0.7513	3.7884	0.7203
Ashas	47	1.034	2.4035	0.3594	0.3801	0.3772	0.3179

Table 8. Prediction equation for data produced by Innogy.

The above equation would probably improve if the data was obtained from the same laboratory sub sample as the scan, however the correlation of 0.94 for predicting the age of the sample is interesting. The two spectra files FR.CAL and SRC.CAL were used in the discriminant analysis part of the software in order to see if the NIR could discriminate between forestry residues and short rotation coppice samples. Table 9 overleaf is the output of this discriminantion. A more detailed explanation of this output is given in appendix B.

Table 9. Discriminant output between FR and SRC spectra

Position	Sample number	Location	fr.cal	src.cal
1	21452097	1	2.174	0.826
2	21452171	1	2.201	0.799
3	21452289	1	2.278	0.722
4	21452192	1	2.014	0.986
5	21452284	1	1.621	1.379
6	21453246	1	1.504	1.496
7	21453758	1	1.554	1.446
8	21454324	1	1.899	1.101
9	21458270	1	1.792	1.208
10	22450265	1	1.782	1.218
11	22451496	1	1.731	1.269
12	21452193	1	1.876	1.124
13	21452285	1	1.861	1.139
14	21453247	1	2.014	0.986
15	21453759	1	1.542	1.458
16	21454325	1	1.823	1.177
17	21458271	1	1.940	1.060
18	22450266	1	1.588	1.412
19	22451497	1	1.747	1.253
20	21452194	1	2.033	0.967
21	21452286	1	1.991	1.009
22	21453248	1	1.836	1.164
23	21453760	1	1.833	1.167
24	21454326	1	1.989	1.011
25	21458272	1	2.208	0.792
26	22450267	1	1.626	1.374
27	22451498	1	2.189	0.811
28	21452195	1	2.044	0.956
29	21452287	1	1.934	1.066
30	21453249	1	1.984	1.016
31	21453761	1	1.967	1.033
32	21454327	1	2.199	0.801
33	21458273	1	2.128	0.872
34	22450268	1	1.641	1.359
35	22451499	1	2.004	0.996
36	21452196	1	1.935	1.065
37	21452288	1	1.948	1.052
38	21453250	1	1.826	1.174
39	21453762	1	2.079	0.921

40	21454328	1	2.172	0.828
41	21458274	1	2.310	0.690
42	22450269	1	1.809	1.191
43	22451500	1	2.034	0.966
44	21452095	2	1.172	1.828
45	21452096	2	1.139	1.861
46	21452098	2	1.328	1.672
47	21452172	2	0.953	2.047
48	21452187	2	1.091	1.909
49	21452279	2	1.282	1.718
50	21453241	2	1.095	1.905
51	21453753	2	1.013	1.987
52	21604441	2	1.380	1.620
53	22450270	2	1.178	1.822
54	22451787	2	1.215	1.785
55	21452173	2	1.013	1.987
56	21452188	2	1.159	1.841
57	21452280	2	0.950	2.050
58	21453242	2	0.779	2.221
59	21453754	2	1.069	1.931
60	21604442	2	0.811	2.189
61	22450271	2	0.978	2.022
62	22451788	2	1.183	1.817
63	21452174	2	1.103	1.897
64	21452189	2	1.117	1.883
65	21452281	2	1.011	1.989
66	21453243	2	1.096	1.904
67	21453755	2	0.951	2.049
69	22450272	2	1.312	1.688
68	21604443	2	1.000	2.000
70	22451789	2	1.376	1.624
71	21452175	2	1.084	1.916
72	21452190	2	1.104	1.896
73	21452282	2	0.949	2.051
74	21453244	2	1.252	1.748
75	21453756	2	0.977	2.023
76	21604444	2	1.273	1.727
77	22450273	2	1.141	1.859
78	22451790	2	0.787	2.213
79	21452176	2	0.967	2.033
80	21452191	2	1.059	1.941
81	21452283	2	0.928	2.072

82	21453245	2	1.137	1.863
83	21453757	2	1.078	1.922
84	21604445	2	1.302	1.698
85	22450274	2	1.065	1.935
86	22451791	2	0.627	2.373

fr.cal	43	0
src.cal	0	43
Totals	43	43
Misses	0	0
Uncertain	3	0
Hits	40	43

The above output shows that the NIR can discriminate between wood of FR and SRC origin. All of the SRC samples have been correctly identified as belonging to the SRC group with 43 out of 43 hits. 40 of the 43 FR samples are correctly identified. FR has samples with 3 uncertains. Figure 30 below demonstrates a perfect discrimination between the two groups.

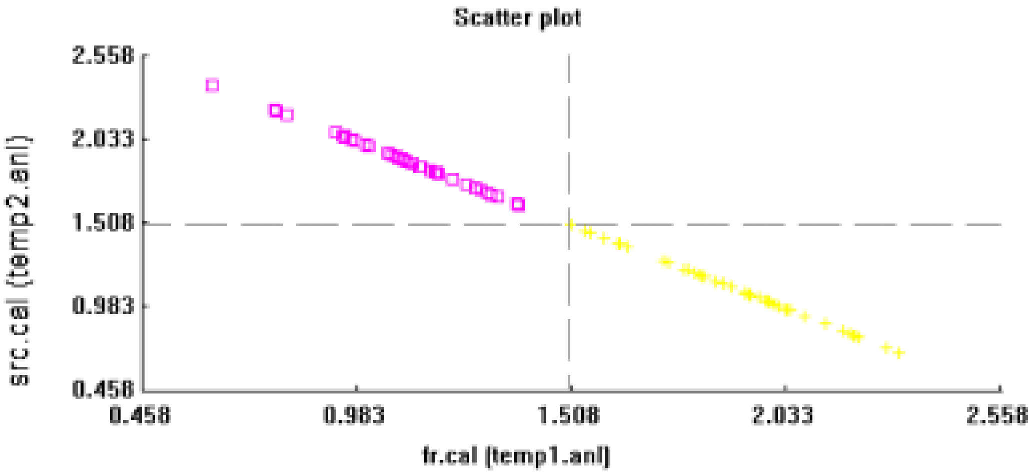


Figure 30. Plot of SRC vs FR 45 degree line indicates perfect discrimination

4.9 Bulk density

During pile construction each load of wood chip was sampled and the moisture and bulk density were measured. The average dry bulk density of forestry residue and SRC wood chip was 220odkg/m^3 and 154odkg/m^3 respectively (see tables A17 &18 in appendix 1 (SRC and forestry residue deliveries)). At the beginning of June 2002 samples of wood chip were collected from three areas of the SRC and forestry residue piles, the top, the centre and a bulk mixture of the two. The dry bulk density of these samples was measured and showed that in both instances the centre of the piles was much denser than the surface. The difference between the centre and the surface was 38.4kg/m^3 in the SRC pile and 43.7odkg/m^3 in the forestry residue pile (see table 10). Further investigation of this finding was required and systematic sampling of both piles was conducted two weeks later. The results from these measurements produced a slightly different outcome (see figures 31 and 32). The relationship between the chip depth and the bulk density for the SRC wood chip was less clear cut, largely as a result of the surface layers sampled having a higher bulk density. The trend relating the chip depth and dry bulk density in the forestry residue pile was similar to the values shown in table 10. A difference of 46.91odkg/m^3 was recorded between the surface and the deepest samples. The average dry bulk density of the wood chip in June was predictably lower than when it was first delivered to the storage site - 125.24odkg/m^3 for SRC and 202.11odkg/m^3 for FR.

Origin	Sample location	Dry bulk density (odkg/m3)	Standard deviation
SRC	centre	135.56	3.35
	surface	97.20	7.80
	mixed	135.31	7.94
	average total	123.95	
FR	centre	227.22	4.18
	surface	183.57	3.09
	mixed	209.90	4.99
	average total	207.20	18.36

Table 10. Preliminary bulk density measurements at different depths in the forestry residue and the SRC piles

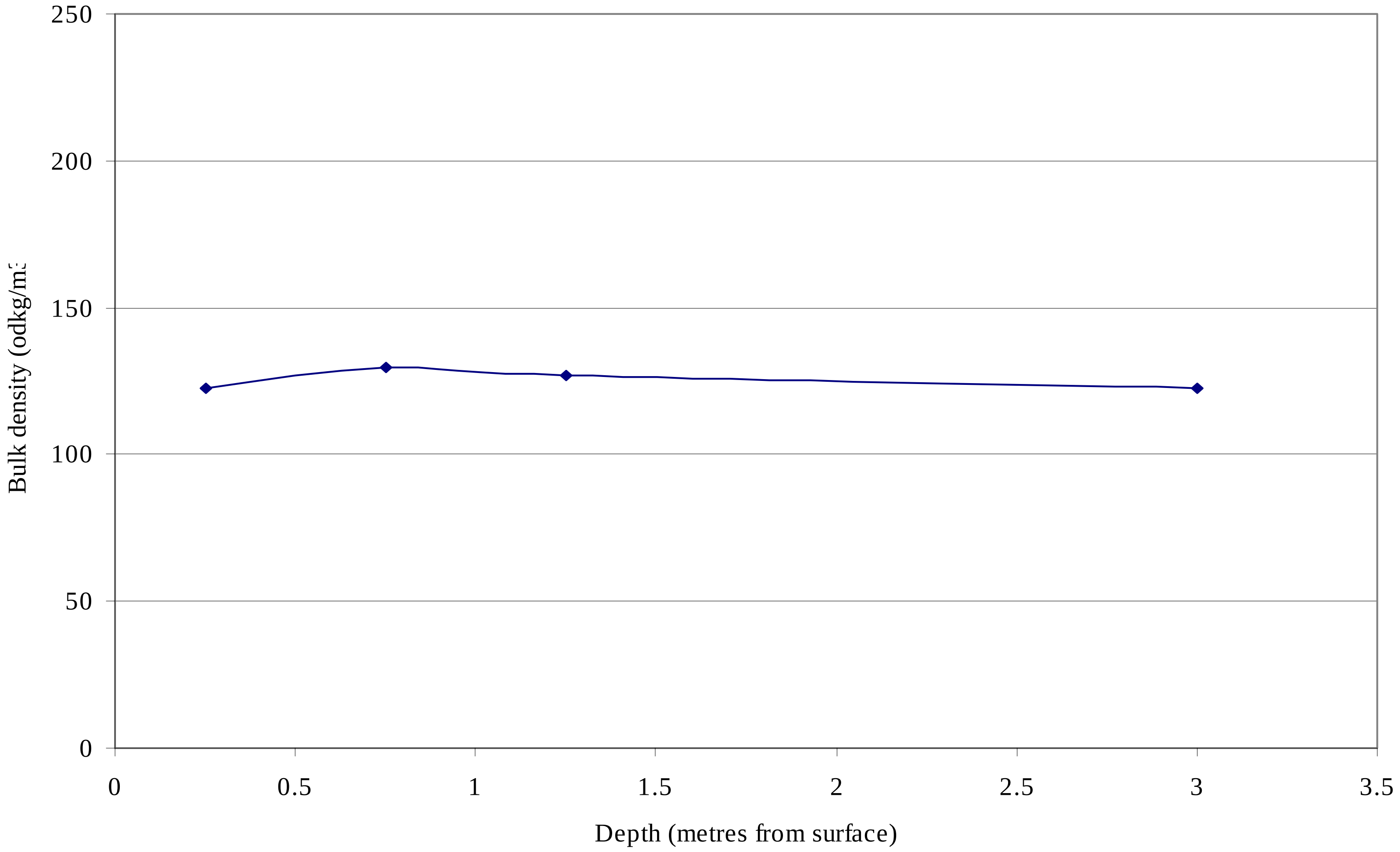


Figure 31. Bulk density of wood chip measured at different depths in the SRC pile

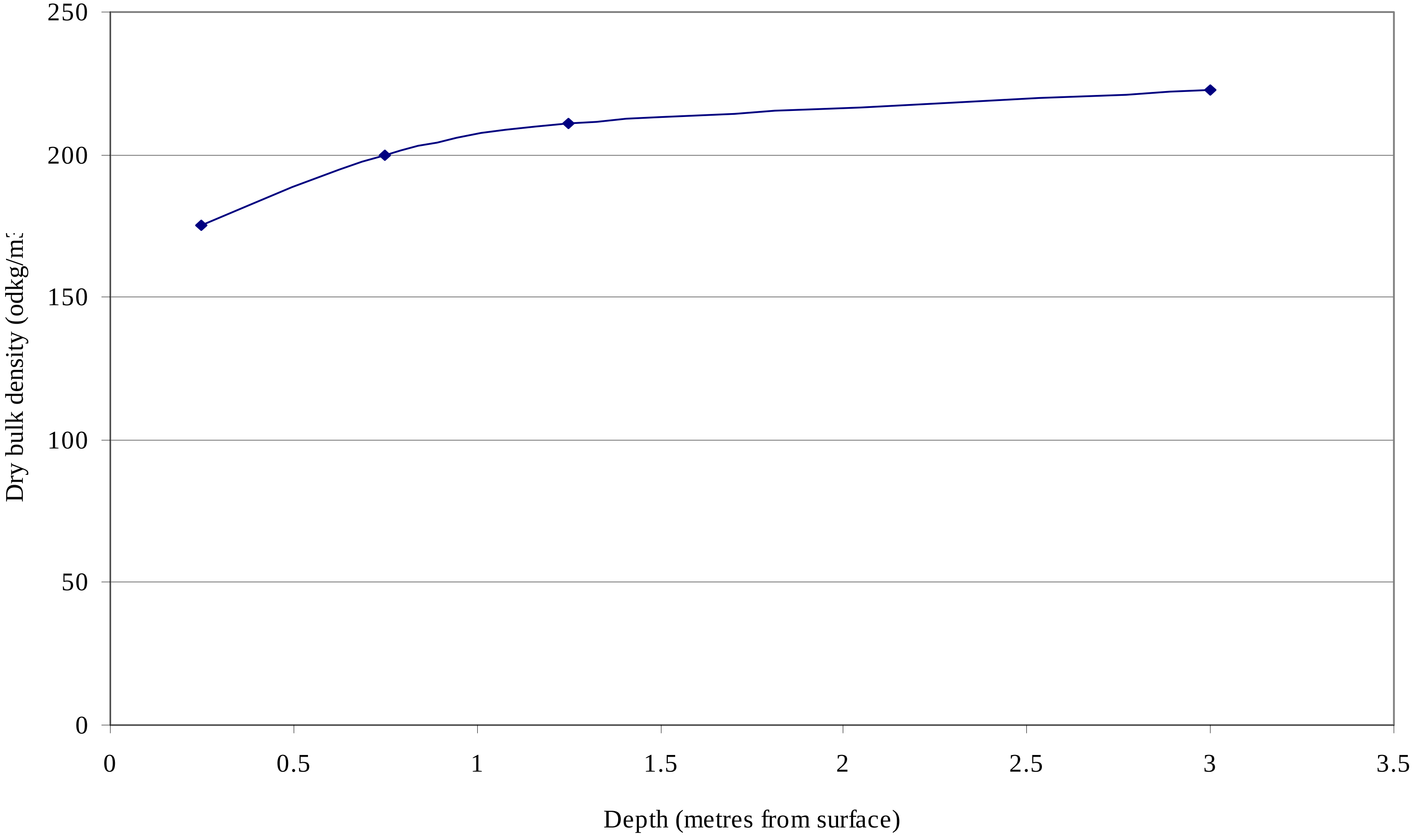


Figure 32. Bulk density of wood chip from different depths in the forestry residue pile

4.10 Airflow and computational fluid dynamics modelling

4.10.1 Density

The results of the bulk density measurements carried out for the air flow modelling are shown in table 11.

Material	**Density wet kg/m3**	**Drymatter %**	**Density dry kg/m3**
Forest Residue	376.6	44.2	166.5
Forest residue	351.0	55.4	194.4
Short rotation coppice	238.4	50.8	121.2
Short rotation coppice	202.2	52.9	106.9
Austoft 10cm SRC chips(2)	299.0	86.8	161.0

Table 11. Bulk density measurements of wood chip used for the airflow modelling

The Austoft sample is from previous work and confirms that the results measured here are in the range observed in previous studies.

The physical volume of the material does not change dramatically during storage. The bulk density of the drymatter remains constant. The model does not need to take shrinkage into account.

4.10.2 Air flow

Results from horizontal and vertical flow from tests were fitted to a power function of the form

$$dp/dh = k * v^n$$

dp/dh	Pressure gradient	Pa/m
v	velocity	m/s
k & n	constants	

Material and Test	**k**	**n**	**R^2**
Forest residue Vertical	1976.9	1.32	0.9988
Forest residue Horizontal	1401.4	1.36	0.9989
SRC Vertical	1005.7	1.41	0.9993
SRC Horizontal	626.9	1.42	0.998

Table 12. Resistance to flow constants

4.10.3 Air movement patterns

The starting point for the natural convection model within the bulk is the standard stack effect ventilation processes. Air movement results from natural convection. The density of air is affected by temperature and humidity. Interstitial air temperature and humidity equilibrates with the solid phase. Vertical and horizontal resistance influences air flow rate and heat flux in the different directions. Height of stack affects convection force. Horizontal air movement affects height of neutral buoyancy plane.

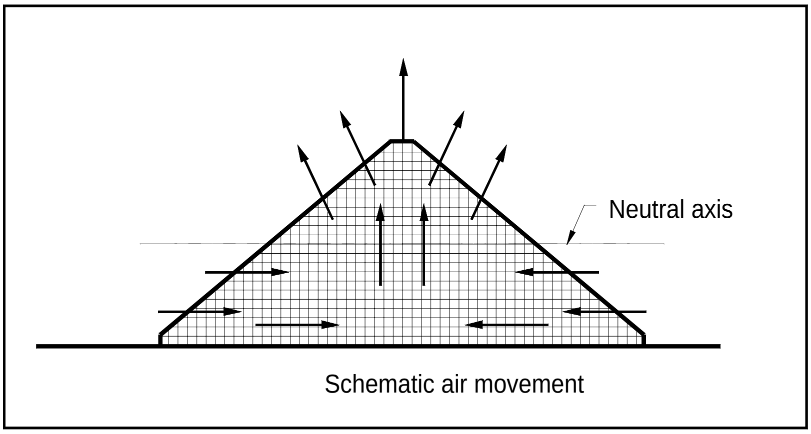


Figure 33. Model air movement paths

4.10.4 Heat flow and drymatter loss

Stack temperature distribution is the most practical indicator of heat flux in the bulk. Figure 34 illustrates a snapshot of the predicted distribution of stack temperature. Figure 35 compares the model results with the average observed stack temperatures.

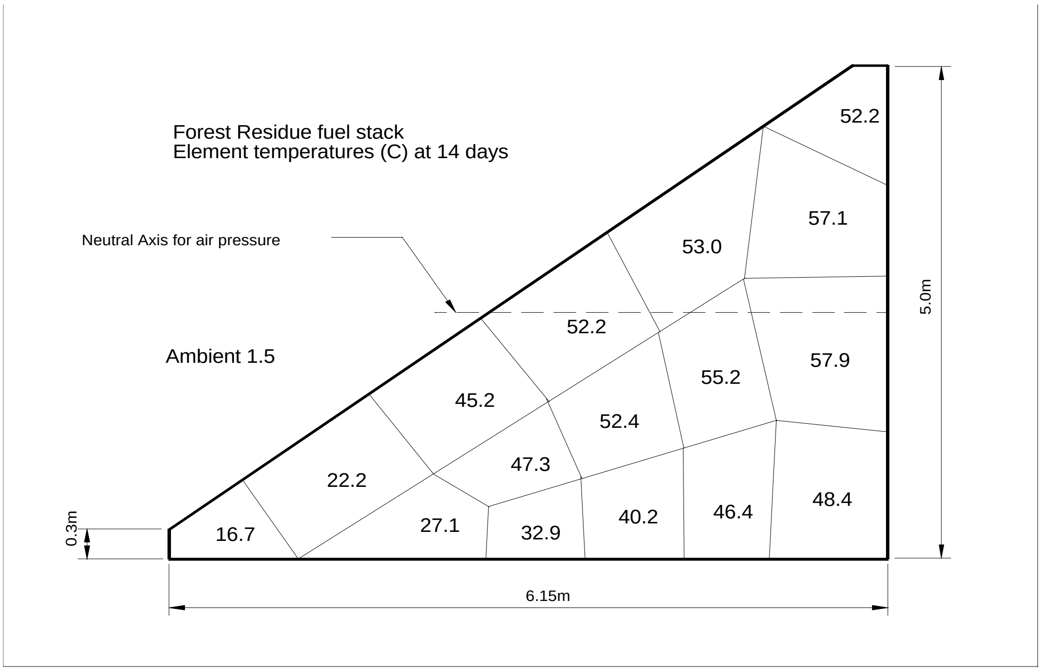
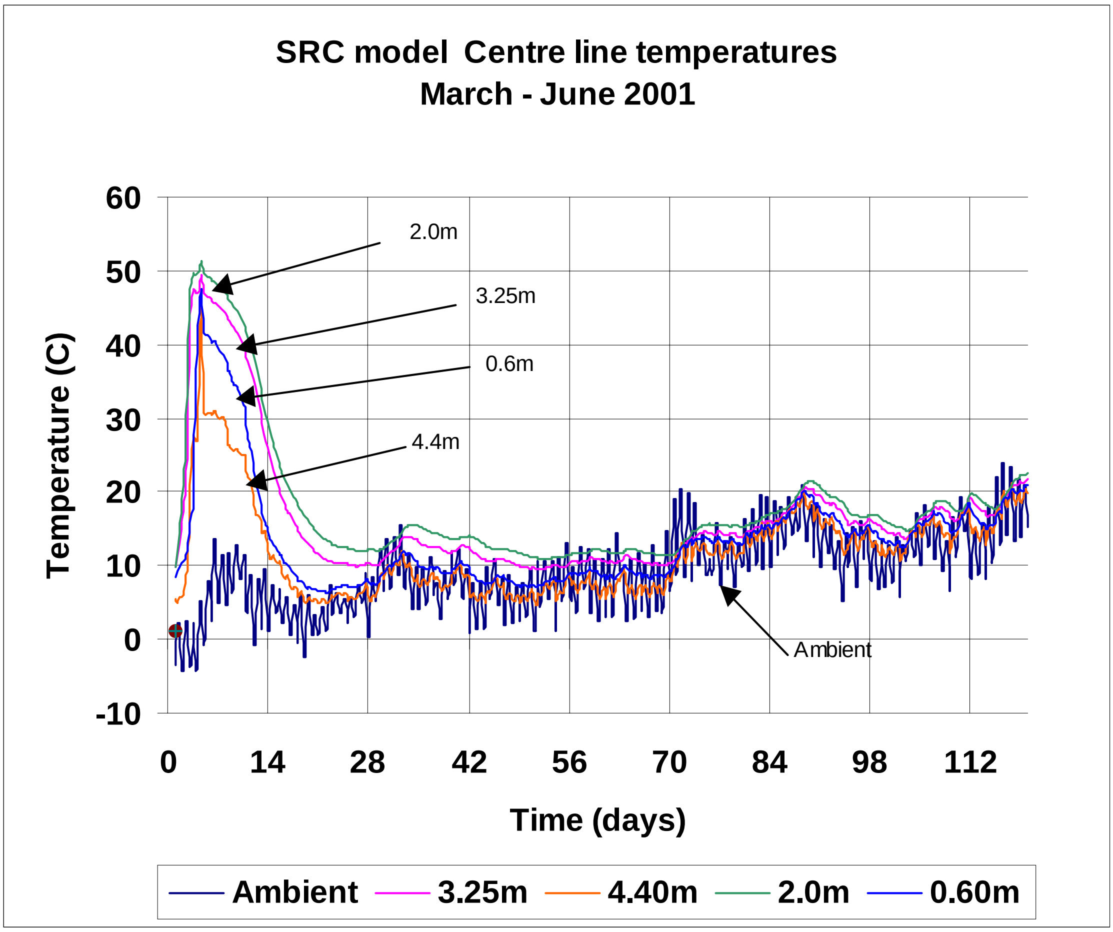


Figure 34. Model temperature profile of a fuel heap



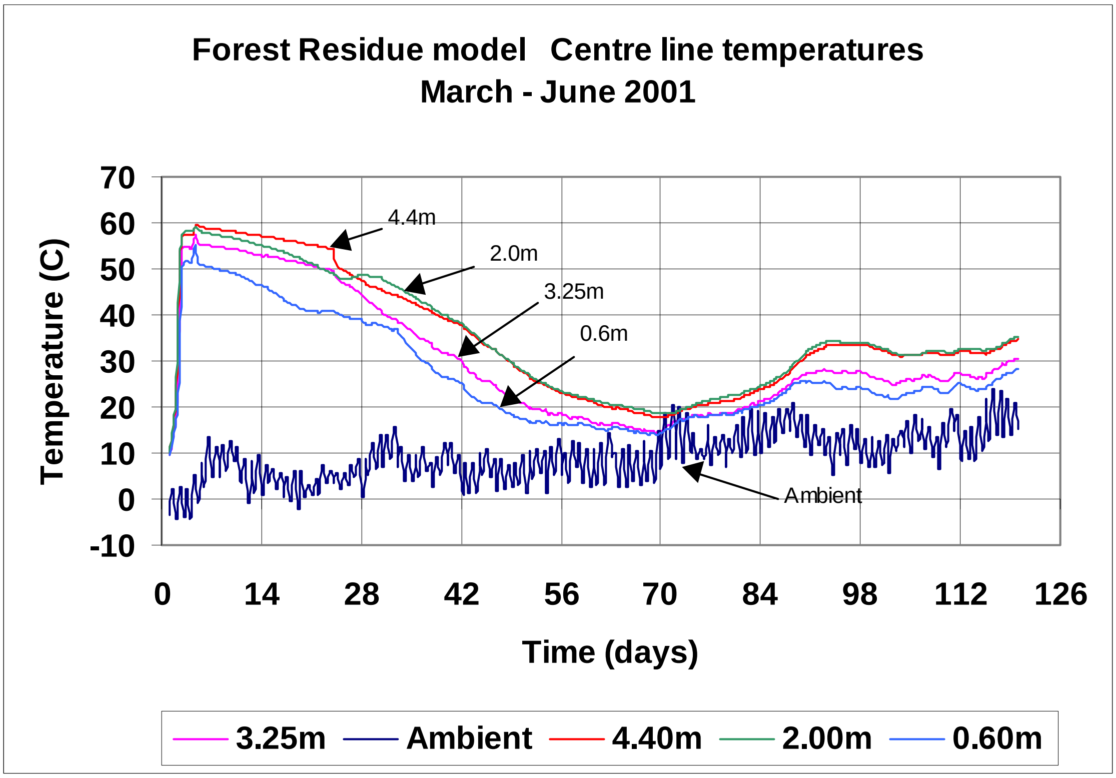
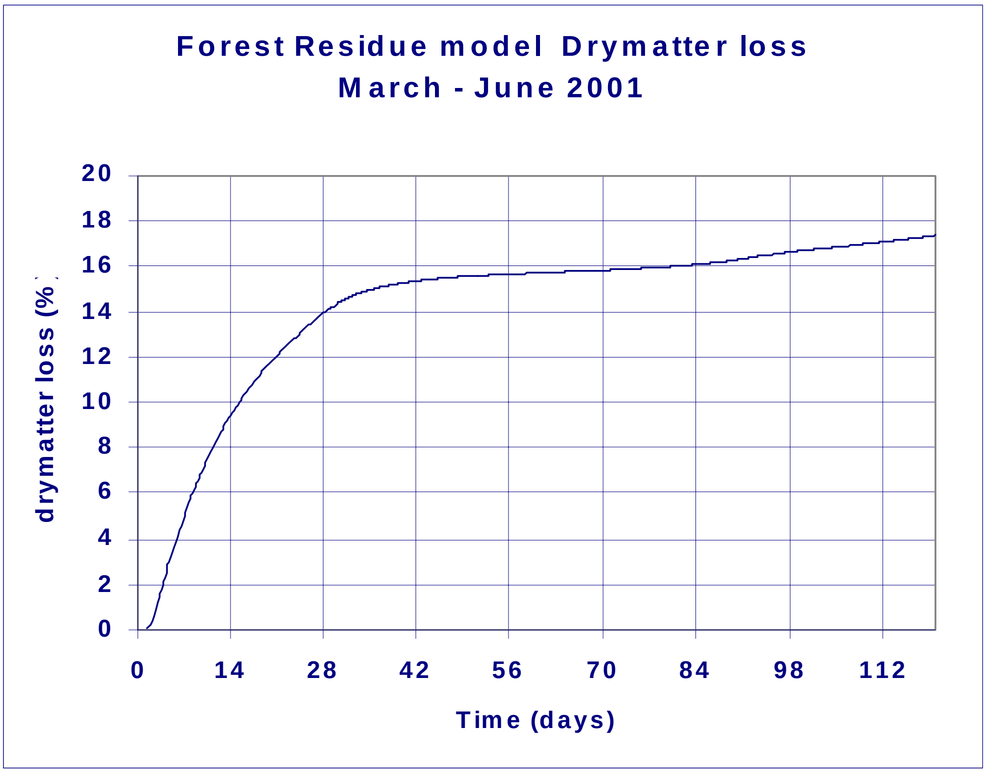


Figure 35. Comparison of measured and modelled stack temperature

Drymatter losses and heat production are based on a model given by Nellist *et al*.(2) The estimated drymatter losses during storage are plotted in Figure 36.

Forest residue drymatter loss plot



Drymatter loss SRC

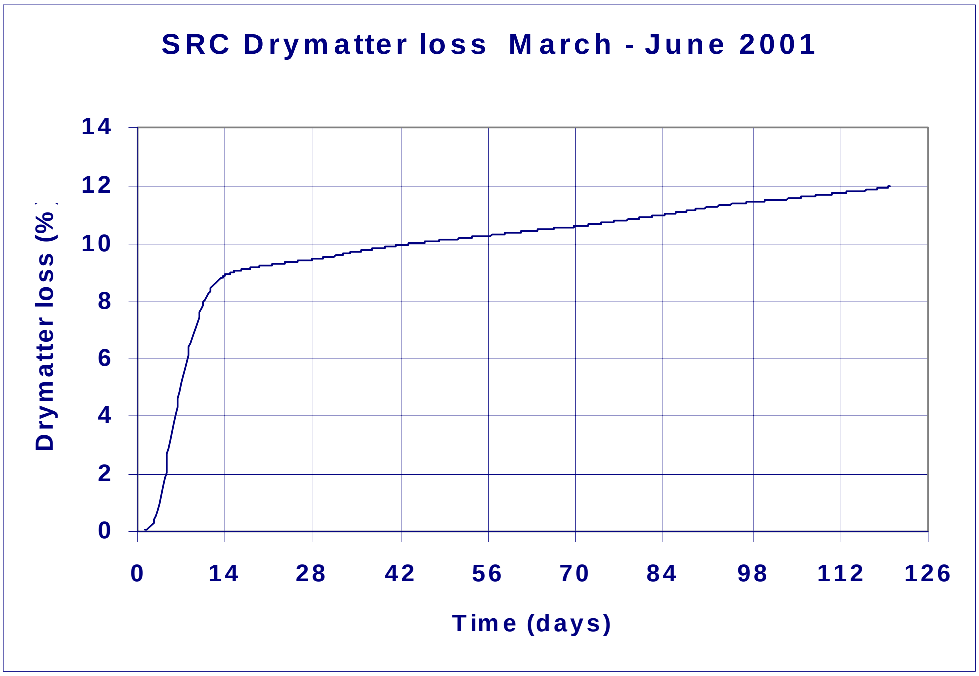


Figure 36. Model estimated drymatter losses during storage

Model results show that most heat transfer is by latent processes. Conduction is relatively unimportant. The thermal conductivity values for the material was estimated from published data for wet cork (IHVE 1970). The specific heat of wood fuel is not reported in the literature so an estimate of this property was made using Sibels formula which makes the specific heat a function of the moisture content.

4.11 Spore measuring and dust monitoring

The results from the spore measurements, 10metres downwind and 50metres upwind of the piles can be seen in table 13. The data is presented as the number of colony forming units (CFU) per metre cubed of air. Each colony forming unit represents one micro-organism in the original sample. The sampling period was determined in accordance with previous ADAS research.

The weather conditions on the day of sampling were generally warm and mild. The average temperature was 21.6^{o}C; the average humidity was approximately 77% (although this fluctuated throughout the monitoring period); there was no rain; the average wind speed was 3.0 m/s and the wind direction was N / NNW.

Chip type	position	flow rate (l/min)	Thermophilic. *Actinomyctes* (cfu/m^3)	*4.11.1.1.1.1 . Fumigatus* (cfu/m^3)	Moulds at 37^{o}C (cfu/m^3)	Moulds at 25^{o}C (cfu/m^3)
forestry	10 downwind	18	<106	n/a	n/a	n/a
forestry	10 downwind	18	<267	n/a	n/a	n/a
forestry	10 downwind	18	n/a	0	n/a	0
forestry	10 downwind	18	n/a	<17	<17	n/a
control	10 downwind	18	n/a	0	n/a	1
control	10 downwind	18	n/a	0	1	n/a
none	50 upwind	18	>194	n/a	n/a	n/a
none	50 upwind	18	0	0	<17	n/a
SRC	10 downwind	18	>244	n/a	n/a	n/a
SRC	10 downwind	18	<155	n/a	n/a	n/a
SRC	10 downwind	18	n/a	0	n/a	>83
SRC	10 downwind	18	n/a	<39	<39	n/a
SRC	10 downwind	18	n/a	>11	n/a	n/a
SRC	10 downwind	18	n/a	0	n/a	n/a
SRC	10 downwind	18	n/a	50	n/a	n/a
SRC	10 downwind	18	n/a	<6	n/a	n/a

Table 13. Concentration of air-borne micro-organisms around the forestry residue and the SRC piles after 15 months in storage

The dust monitoring results were as follows:

	Teleporter driver	**Interim sampler**	**Aerosol sampler**	**Static sample points**
Time (minutes)	171	158	171	176
Flow rate (litres/minute)	2	2	2	2
Exposure level (mg/m^3)	0	0.32	0	0.28

Table 14. Dust monitoring results from the Great Heck storage site

5 DISCUSSION

5.1 Wood fuel storage

The main hypothesis being tested in these trials was that the heat generated within the piles of wood chip by biological reactions was capable of producing adequate natural drying for the fuel to be suitable for direct power station use. Unlike the provision of drying through external energy use and forced ventilation, the cost of this passive drying is the dry matter lost in store, and the efficacy of the drying is affected by the rainfall. Overlying this drying from internal heat production is the production of volatile fatty acids (VFAs) from fermented water soluble carbohydrates (WSC), leading to a low pH environment that may provide some protection against excessive dry matter loss.

5.1.1 Moisture content

The dry matter results in this study are characterised by a decline in the moisture contents of material stored at a depth of 1.5m or more within the stack. Although material stored at shallower depths at times matched the moisture content of these deeper samples, there tended to be greater fluctuation in the values. The SRC was loaded at around 52% moisture, and after 450 days the surface layers had risen to 68% moisture and the material at 3m depth was just above 30% moisture. The respective values for the Forest Residue (FR) material were 40% at loading, and 61% on the surface and 26% at 3m depth by the end of the trial. These figures are similar to those obtained by Nicholls and Feng (1992) using 450tonne piles during a 3.5 month period starting in January 1990; the surface layers rose to about 65%, whilst the core samples 4.5m in the stack fell to 35% moisture.

The rainfall during the storage period put 650kg of water on to each square metre of the store. The Potential Transpiration for this area of the UK (MAFF 1976) is 486mm (*c.* 486kg/m^2), which equates to just over 600mm in the 15 month storage period, and although moisture loss from a heaped and rough surface may not be equivalent to transpiration processes, these values show that weather conditions produce significant scope for evaporative loss. The moisture content and drying performance of the surface layers appear to limit the overall drying process.

The accumulated rainfall shown in figure 37 is characterised by a steeper increase in the water input during the autumn (after day 200). This matches increases shown in the moisture content in figures 9 and 10 in samples between day 200 and 300 of the storage period. The construction of the stacks by pushing up the chipped material with a loader bucket leads to the random formation of layers and bands of fines within the heaps. It is unclear to what extent this affects moisture permeation but the graphs suggest moisture movement in to the top 1m is not uniform.

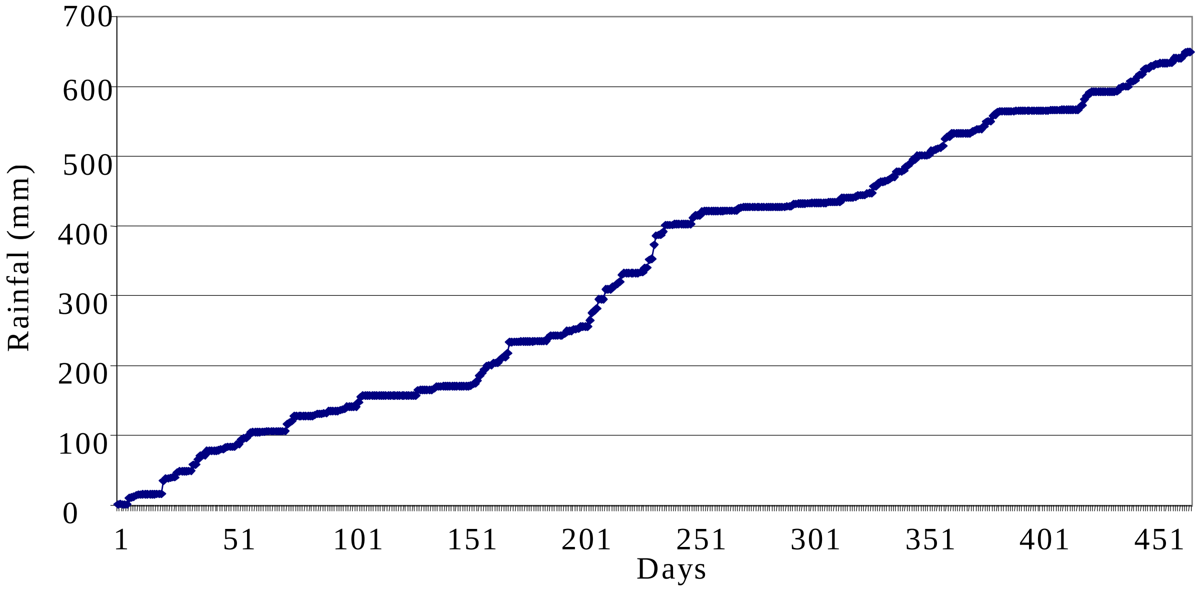


Figure 37. Accumulated rainfall, March 2001 - May 2002

The “wet lens” concept suggested by Buggelen (1999) is a feature of stacks that would help to account for this variability of moisture, acting as a moisture ‘holding area’ into which moisture is driven by heat from the lower stack, and subsequently removed by evaporation from the top and shoulders of the heap.

5.1.2 Ash Content

As total ash in the store is unchanging, any significant reduction in the biologically active dry matter through respiration and fermentation will result in an increase in the ash percentage. This increase is irreversible. If the mean ash percentage in all samples are regressed against time the tendency of the linear trend is to shows a slight increase in percentage ash in the dry matter. The linear plots are shown below. The r^2 value for the forest residues is possibly a reflection of the variation in ash levels of the incoming material.

SRC………………………………y = 0.0032x + 1.6089 (r^2 = 0.4524)
Forest Residues………………… y = 0.0025x + 1.7798 (r^2 = 0.2701)

If the annual increase in ash in the dry matter is from 1.5% to 2.5%, this represents a 40% loss of dry matter over the 15 month period or 2.7% per month. This is well under the 6% monthly loss cited by Nellist *et al* (1994) for the unventilated storage losses of willow. Sanderson, Egg and Wiselogel (1997) quote a 13% loss over six months (2.2% per month) from material baled in August. This is less than the present losses, and although cutting in August would increase likely losses through respiration and green material breakdown, baling would provide a more secure storage system than heaps open to the weather.

5.1.3 Calorific value

The calorific values for both SRC and FR are shown in figures 13 and 14 represent the energy contents of material ex store, with most of the variation caused by changes in moisture content. Indeed the lower CV of the material from 0.1m in the stack mirrors the moisture levels shown in figures 9 and 10

The net energy in the dry matter remained relatively consistent (Appendix A showing dry ash free [DAF] calorific value). Although the CV will fall as dry matter losses increase the percentage of non combustible ash in the fuel, the loss of dry matter and the moisture content will have a greater effect on the overall efficiency and economics of the plant than lower energy levels caused by the slight increase in ash content.

The moisture content is the main factor to be controlled in delivery of the fuel to the plant.

5.1.4 Temperature

Despite various short term and zonal temperature variations within the stacks the unequivocal trend for both SRC and FR is a rapid rise in temperature after loading, followed by a gradual decline over six months to temperatures between 5 and 15ºC above ambient. The peak temperatures were between 50 and 60ºC in the stack surface layers, and between 60 and 70ºC in the core of the heap.

The peak temperatures were only held for a very short interval, after which the stacks cooled. The very low and infrequent occurrence of samples with detectable acetic acid levels suggest the temperatures were neither high enough nor held for long enough to allow the splitting of acetyl groups from the cellulose. The acetic acid levels shown in table 3 in the review section of this report, are from 12 month old heavily compacted material that had heated, and was unable to dissipate heat as fast as the stack break down was producing it. The highest acetic acid level recorded in the present study was 709mg/kg, compared to 5440mg/kg produced in the compacted stack.

The fall in stack temperatures indicates an initial flush of fermentative activity at loading, after which the stored material no longer had sufficient rapidly available energy sources to power endogenous heat generation. After about six months there appears to be sufficient biological activity to keep the internal stack temperature at around 10-15^{o}C above ambient (Figures 15 and 16). Stack temperatures tended to fall in winter, and surface layer temperatures, particularly those of the SRC stack, fell below 10^{o}C. The FR had higher temperatures, with the core temperatures frequently above 20^{o}C.

The FR stack was slightly smaller with an average height of about 4.5m compared to around 5m for the SRC, but such relatively small differences would have been negligible in their effect on the radiative and evaporative surface area of the heaps. Small heaps have a higher surface area per unit of volume, so will tend to be cooler. In much larger stacks than those in this study Fuller (1985) showed as stack heights increased from 15m to 22m and 30m, so the internal equilibrium temperature increased significantly for each increment in height

Although the SRC showed the greatest initial lift above ambient, higher initial water soluble carbohydrate (WSC) and more lactic acid production, the FR appear to have sustained a higher level of subsequent temperature. This could be due either to a higher rate of heat production within the FR pile or a lower rate of heat loss. The rate of heat loss is related to the ease of air flow within the stack.

5.1.5 Air flow and computational fluidised dynamics modelling

Convective air movement within the bulk is the most important mechanism for the transfer of heat within a bulk chip pile. Respiration results in the production of heat and moisture which makes the air within the bulk less dense than outside ambient. Buoyancy forces cause the warm air to rise out of the heap and draw in cool air from the sides and bottom. When ambient temperature conditions are reversed the flow direction in the heap may reverse.

The resistance of the bulk material to air flow and the height of the stack will affect the maximum temperature reached. It was found that in order for the model to predict the observed temperatures it was necessary to use higher air flow resistance parameters. This is consistent with higher packing density in the heap and the blockage of interstitial spaces by break down products and, near the surface, rain water. The development of fungal hyphae in undisturbed material would also be expected to increase the resistance to air flow.

Air movement caused by wind pressures will affect stack temperature but the penetration of these effects is probably restricted to the edges of the bulk.

Conduction between elements plays only a minor part in the heating and cooling of the stack.

5.1.6 Biochemical changes

The material from SRC showed a higher WSC level at loading, higher initial production of lactic acid, and a more prolonged decline. Although the conditions in large stacks of wood chip are very variable, fermentation products like lactic and acetic acid can volatilise or be removed in drainage effluent (although none was seen in either stack) or be broken down along with ATP by other processes within the stack to produce water and CO_2. In essence the material oxidises away, and if heat dissipation is inadequate the oxidation processes lead to combustion. In both the SRC and FR stacks heat dissipation avoided a marked increase in temperature, although the FR material generated more heat and the increase in lactic acid levels after about 4 months in store indicates renewed fermentative activity possibly on breakdown products of cellulose. The higher levels of lactic acid in the upper layers of the stacks would support both the dissipation by volatilisation from the upper layers and the breakdown of lactic acid retained in the lower layers.

The main process appears to be a short term, fermentation driven, temperature rise leading to VFA production. This is then followed by a cooling, and dissipation of VFAs produced. During this period the uncovered stacks showed some drying of the internal mass, whilst the outer layers were wetted and dried on a cyclical basis driven by the weather. The extent of the fermentation is directly related to the WSC content, and inversely related to the degree of lignification. Following from this, the higher the initial fermentation activity the greater the subsequent loss of dry matter and decline in bulk density; less lignified tissue tends to be younger and have higher WSC levels, and it thus more prone to speedier breakdown in store.

Overall, the levels of VFA arising from WSC fermentation were relatively low, and although they are indicative of a loss of dry matter through fermentation the maximum value of just below 3000mg/kg would not contribute to significant error in dry matter determinations as suggested by Jirjis (1995).

5.1.7 Near-infrared Reflectance Spectroscopy

NIRS has considerable power for discrimination in wood materials. Atkinson, Jervis and Sangha (1997) successfully identified different Birch species and their hybrids from ground foliage and petiole material. In this study the results show good degrees of correlation between NIRS data and wet chemistry values for dry matter, lignin, cellulose, ash, WSC and pH. The technique therefore has potential for use at reception to differentiate between materials of different fermentation potential. In most circumstances early cut green sappy material could easily be identified visually. However where material is cut late in the winter/early spring, say after wet over-winter ground conditions, NIRS would allow loads high in WSC to be identified. The technique is widely used for point-of-intake checking of cereals and similar material going into food manufacture.

How high WSC material is stored (blended, or separately for short periods) requires further study. Similarly with a greater body of data NIRS may be able to differentiate between lignin and cellulose characteristics that predict break down in store. With the exacting fuel standards of the ARBRE BIG-CC power plant NIRS could provide further information of use in the management of the fuel supply.

5.1.8 Particle size distribution

The samples showed a lot of variation in the size fractions and although the plots of sizes in figures 23 and 24, do not indicate a marked increase in the fines (<3mm) fraction, reactions occurring in store can cause this to occur. Material stored for over two years at another storage site has shown a considerable increase in fines. However this material has reached higher temperatures at which cleaving of acetyl groups from cellulose has occurred, as shown by the strong odour and the discolouration of the chips. This may have had a marked effect on the mechanical strength of the wood.

Changes in the harvesting procedures of SRC and the type, size and efficiency of chippers used on FR before delivery will have a marked effect on both the initial proportion of fines in the material, and the subsequent break down of material in store. Changes in the harvesting procedure for ARBRE SRC are likely to change the proportion of fines and their rate of production, such that the particular data presented here are less relevant to the future operation of the plant. Nevertheless the principles established will still guide storage practice.

5.1.9 Bulk density

The chipped hardwood from broad-leafed woodland has a higher dry bulk density than the chipped SRC. The principal change in bulk density of stored wood chip occurs in the wet bulk density, due to variation in moisture content.

A variation in the dry bulk density is indicative of either a change in the particle size distribution or a loss of dry matter. A break down of material causing a marked increase in the proportion of small particles could lead to an increase in bulk density. In fact a decrease in dry bulk density was observed and no significant variation in the level of fines was seen. The decrease in bulk density is a measure of the loss in dry matter through biological processes. The first set of bulk density measurements made at the end of the trial showed a higher bulk density loss in the surface region than in the core in both piles. This indicates a higher rate of dry matter loss at the surface. It is likely that this is related to drying in the core region. As the core material dries, the rate of biological activity declines whilst biological activity continues at the surface. Fungal mycelium was seen only seen in the wet surface layer which supports this suggestion (see plate 3 below). Subsequent measurements showed this bulk density variation with depth only in the FR pile.

Plate 3. Fungal growth and subsequent chip degradation of SRC wood chip

The white areas near to the surface of the pile are the regions infested with fungal growth.

The SRC material showed a decrease in bulk density over the trial period of 19.9%, equivalent to a dry matter loss of around 1.3% per month, neglecting ash content. The implied rates of dry matter loss for the forestry residue stack at different depths are shown in table 15 below.

Depth (/m)	% dry matter loss over trial	Monthly % dry matter loss
0 - 0.5	20.2	1.3
0.5 - 1.0	9.2	0.6
1.0 - 1.5	4.2	0.3
>3.0	0	0
Average	8.4	0.6

Table 15. Dry matter loss for forestry residue chip at different depths in the pile

These dry matter loss figures are low compared to those quoted in other studies, and about half that estimated from the change in ash content. However the regression analysis on the ash data did not indicate a strong correlation of ash content with time.

5.1.10 Spore measurements

Interpretation of the spore monitoring data revealed that the handling of the wood chips only marginally increased levels of air-borne microoganisms. It is important to note that both the SRC and the forestry residue piles were only disturbed for approximately 5 minutes, whereas the samples were taken over several hours. A prolonged period of activity may have resulted in more micro-organism being released into the atmosphere.

The upwind concentration of thermophilic *actinomycetes* was 194 cfu/m^3, while the average downwind concentration was 193 cfu/m^3, indicating that movement of the piles did not increase the concentration of this organism in the environment. It may also indicate that the piles were not inhabited by this particular organism at this time, possibly due to the cooler core temperature up to and during this time of year (December to June) which do not favour thermophilic species. The number of *Aspergillus fumigatus* increased significantly downwind of the wood chip piles (the upwind sample point recorded 0 cfu/m^3; the downwind sample points recorded up to 17 and 50 cfu/m^3 from the forestry residue and the SRC piles respectively) indicative of its presence within the piles.

It is important to note that all the levels of airborne microorganisms are very low in comparison to other operations that produce bioaerosols. Composting has been the focus of much research, with regard to the health impacts of *A fumigatus*. During composting operations it would not be unusual to find levels above 600 cfu/m^3 during handling. Likewise levels of thermophilic *Actinomycetes* higher than 1000 cfu/m^3 are often observed. It is clear that the highest levels observed here, 267 cfu/m^3 for thermophilic *Actinomycetes* and 50cfu/m^3 for *A. fumigatus,* are well below operating levels for composting activities.

It is difficult to draw any conclusions about the differences between the SRC and forestry residue spore contents. It would appear that the SRC wood chip is contributing more *Aspergillus fumigatus* to the atmosphere, but no definitive conclusion can be drawn without further research.

The results from dust monitoring showed very low levels. The teleporter driver in the partially enclosed environment and the bioaerosol monitor operator were not exposed to excess dust; a reading of 0mg/m^3 was recorded. The highest exposure to dust was measured by the personal monitor on the person responsible for interim sampling. The level was 0.32mg/m^3. The static sampler placed downwind also measured similar levels at 0.28mg/m^3. The maximum exposure level for dust is 10mg/m^3 over an 8hour time weighted average (Control of substances Hazardous to health, 1999). Accordingly it can be stated with conviction that the observed levels are safe, particularly since the driver is the most likely person to be exposed during normal operating conditions.

To conclude, during the handling of wood chips a rise in the level of moulds was detected, of which *A. Fumigatus* is of most concern due to its well-publicised detrimental pulmonary health effects. The levels of bioaerosols observed are well below levels that are expected during handling operations during other activities like composting. It is therefore unlikely that handling will cause any significant health impacts to either the general public or workers. The levels of dust observed were well below the Health and Safety maximum exposure levels.

5.2 Power plant implications and recommendations

5.2.1 Plant implications

The critical concerns for power plant operators are:-

- that the delivered wood chip should meet plant specifications;
- that the cost of storage, including any dry matter losses, should be minimised;
- that storage should not give rise to a significant health risk.

The plant wood chip quality specification will typically cover calorific value, moisture content, ash content and particle size distribution. In the case of the ARBRE power plant, the wood chip should comply with the following

- Moisture content < 30%
- Maximum particle size 30mm
- Particles < 3mm in size < 10% of bulk
- Ash content < 2% by mass, dry basis
- Calorific value is largely a function of the moisture content and the ash content and is not specified separately. If the wood chip meets the ash and moisture requirements the calorific value is likely to be acceptable as well.

The particle size distribution did not change significantly during the trial. The chips do not seem to have degraded to produce an unacceptable level of fines. As long as the particle size distribution is acceptable when the chips go into store there is nothing to suggest that they will fail to meet the size specification when they are removed from store. In general the largest average particle size consistent with the power plant specification is to be preferred. This minimises resistance to air flow which encourages drying and reduces the rate of dry matter loss which is partly a function of exposed wood chip surface area.

The ash content did not change significantly during the trial either. In theory a large enough dry matter loss could result in a significant increase in ash content measured on a dry weight basis. This has not occurred to a large enough degree to be quantified with certainty.

The moisture content of the wood chip would be a serious cause of concern to a power plant operator. The results show that the piles are broadly split into two regions, the core region and the surface region. In the forestry pile the moisture content at 3.0m and 1.5m declined to around 30% after about 30 days and remained at around this level for the rest of the trial. In the SRC pile the moisture content was more erratic, but also decreased to around the 30% level at the 1.5m and 3.0m depths over the summer of 2001. The surface layer of the piles averaged around 60% moisture. It is clear that the surface region of both piles remained wetter than the ARBRE plant specification throughout the trial period, while the core region did reach an acceptable moisture content at some points in both piles. The boundary between the wetter surface layer and the drier core region probably moves between the 1.0m and 1.5m depths according to the weather. If the midpoint between the two, 1.25m, is taken as the boundary depth, the fraction of material lying in each region can be estimated.

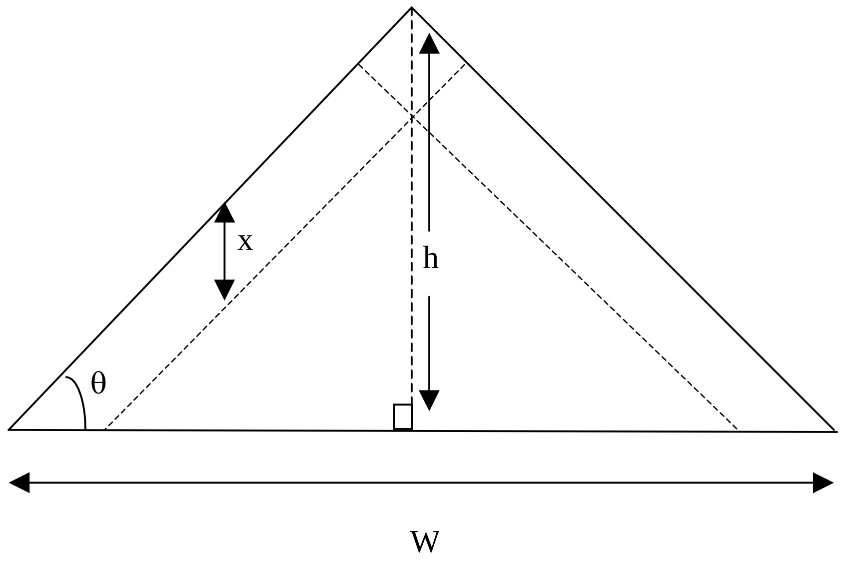


Figure 38. Cross-section of a pile

For a pile of height, h, and width, w, the cross sectional area is given by 1/2.h.w. The cross sectional area of the core region, being the region at a vertical depth of greater than x from the pile surface, is given by [(h-x)/Tanθ].[h-x]. For the SRC and FR piles the cross sectional areas are shown in table 11 below.

		Full pile			Core region				
	Slope angle (degrees)	Height (/m)	Width (/m)	Area ($/m^2$)	Boundary depth (/m)	Height (/m)	Width (/m)	Area ($/m^2$)	Core area as % of full area
SRC	39	5.0	12.3	30.9	1.25	3.8	9.3	17.4	56
FR	37	4.5	11.9	26.9	1.25	3.3	8.6	14.0	52

Table 16. Dimensions of the SRC and forestry residue piles

This shows that only just over half of the material is in the core region where the moisture content reaches an acceptable level. Taking a weighted average of the core and surface material suggests a moisture content of around 45% in both piles.

This shows clearly that pile design needs to maximise the size of the core region. This can be achieved by increasing the height of the pile.

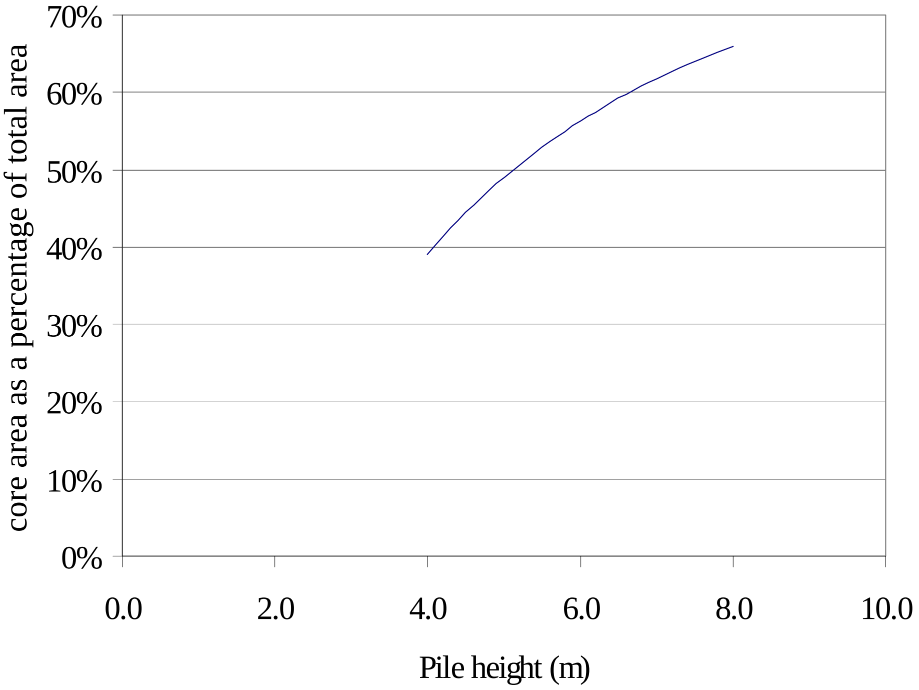


Figure 39. Percentage core area in relation to pile height

Figure 39 shows the effect of increasing the pile height from 4m to 8m, assuming a boundary between core and surface regions of 1.25m. Increasing the pile height will reduce the rate of heat dissipation. However, given that the periods of high temperature were relatively short lived and that pulp mills may build piles to heights of 20m or more, a 8m pile should not present problems. The limited reach of commonly available farm machinery will prevent building piles much bigger than this. Even with an 8m pile, the core region only comprises 66% of the pile. Changing the pile shape to a trapezoid cross section would also increase the fraction in the core region, but might allow greater rain infiltration due to rain ponding on the top surface rather than being shed by the sloped sides. The rate of heat dissipation would again be reduced and the rate of moisture loss from the pile could be reduced by the smaller surface area to volume ratio. A 5m high pile with a 10m wide flat top and a 38^o slope would have a core region of 68.5% of the pile. If the depth of the wet surface region can also be reduced, the proportion will be increased more significantly (see figure 40).

In practice this means reducing the amount of moisture addition by rainfall. Nurmi (1991) suggested the impervious nature of plastic covers encouraged greater dry matter losses and higher moisture levels through the prevention of natural drying. A covering material that will shed most of the rain whilst still allowing relatively free movement of air is required. Woven polypropylene sheeting is a cheap, light strong porous fabric that could shed sufficient rain to prevent significant wetting, whilst allowing water vapour to escape through the weave of the fabric.

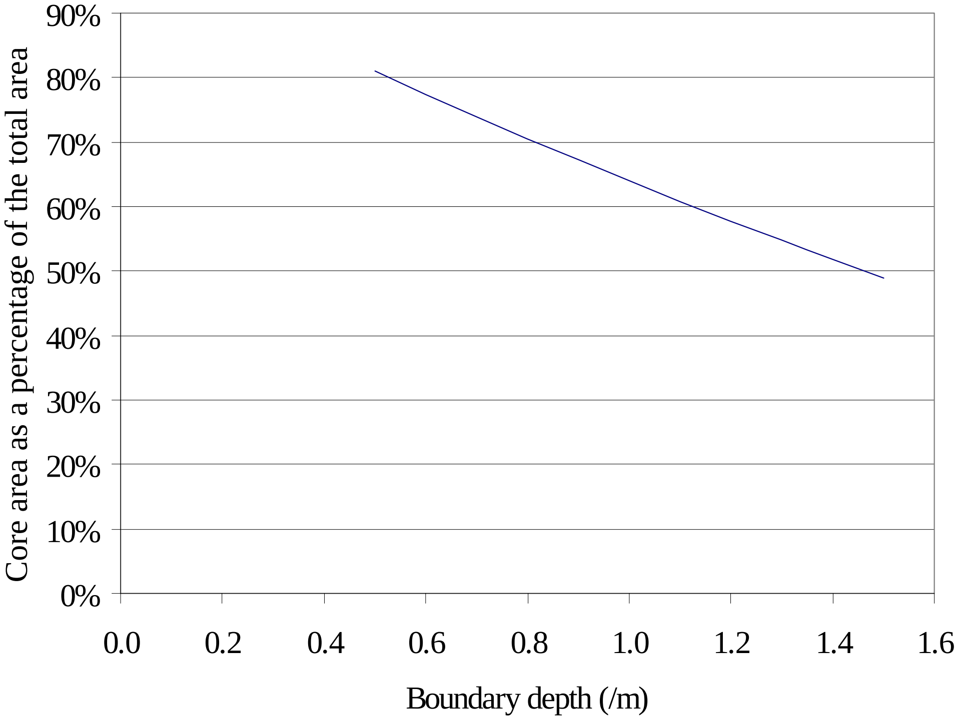


Figure 40. Variation of Core Area Fraction with Boundary Depth

The dry matter loss in the SRC pile, as indicated by the change in bulk density, was around 1.3% per month, or 20% over the course of the trial. Financially this translates to a 25% increase in the fuel cost over the trial period. The corresponding figures for FR are ~0.6% per month or ~8.4% over the trial period equivalent to a 9% increase in the cost of fuel. It is clearly important to minimise the rate of dry matter loss. The wood was actually at its driest after around 60 days in the case of forestry residues or 150 days in the case of SRC. This would be the optimum time to use it. Scheduling the use of wood stocks to minimise the period in store will also reduce the loss of dry matter and hence the overall fuel cost.

Dry matter loss can also occur in a more catastrophic manner. Fires in wood piles are a relatively common phenomenon. They have been experienced at one of the ARBRE storage sites in a pile of wood chips that had been heavily compacted during construction. These compacted piles have had thermocouples buried in them and temperatures in excess of 70ºC have been recorded. 70ºC seems to represent a danger level above which spontaneous combustion may occur. Temperatures in the loose trial wood chip piles used in this study have not reached these danger levels. The air flow measurements and modelling show that convection is the most important mechanism in heat loss. Convection currents will also help in the removal of moisture. Convection is encouraged by a low air flow resistance which in turn results from loose piles, low levels of fines and a larger average particle size. The implication for plant operators is that although piling chips loosely results in larger storage area requirements than for compacted chip piles, it is a less risky strategy.

The spore measurement results did not reveal any significant risk to operators working with stored wood material. However this finding contrasts with commercial operating experience in Sweden where farmer's lung like symptoms have been observed in workers handling wood chips regularly (General Recommendations of the Swedish National Board of Occupational Safety and Health on Organic Dust in Agriculture, 1996).

6 CONCLUSIONS AND RECOMMENDATIONS

1. Natural air drying can reduce wood chip moisture content to acceptable levels without unacceptable chip degradation, but only in the core of a pile where the chips are insulated from the effects of the weather by the surface layer above

2. Chips should be piled loose, rather than being compacted, in order to maximise convective heat loss and related moisture loss.

3. Harvesting and chipping should be optimised to provide a chip with as uniform chip size as possible and with the minimum of fines in order to give a low resistance to air flow. The chip size should be as large as possible consistent with the handling equipment at the power plant.

4. Piles could be built higher than the piles in this study to increase the core: surface ratio. However piles should not be built so high that there is a danger of temperatures reaching levels at which spontaneous combustion may occur. Based on this work, and literature, a 10m pile height would seem reasonable if machinery allows.

5. Alternative pile shapes, which increase the core: surface ratio, should be considered. CFD modelling may give an insight as to whether alternative shapes will still allow adequate air flow.

6. Covering materials that will shed a large proportion of rainfall while still allowing plenty of air movement should be investigated.

7. Careful scheduling of material removal from store can minimise the amount of dry matter loss.

8. No evidence of a significant health risk arising from exposure to wood dust or fungal spores during routine operations was found. However, based on experience in Sweden, precautions should be taken in handling wood chip that has been in store to minimise exposure.

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APPENDIX 1

Table A17. Deliveries used to construct the SRC pile

Delivery Date	Haulier	Weight ticket no.	Delivery ticket no.	Fresh weight (/te)	Moisture content (%)	Dry weight (/odt)	Grower
5-Feb-01	J W Maeer	132(AEL)	51571	23.52	59.41	9.55	YW ES-97
5-Feb-01	J W Maeer	131(AEL)	51570	23.7	58.94	9.73	YW ES-97
28-Feb-01	J W Maeer	159(AEL)	51135	21.52	52.76	10.17	YW ES-97
28-Feb-01	J W Maeer	160(AEL)	51136	23.88	57.34	10.19	YW ES-97
28-Feb-01	J W Maeer	161(AEL)	51137	22.34	55.26	9.99	YW ES-97
2-Mar-01	J W Maeer	165(AEL)	51291	18.1	51.35	8.81	YW ES-97
2-Mar-01	J W Maeer	167(AEL)	51293	16.14	57.17	6.91	YW ES-97
5-Mar-01	J W Maeer	171(AEL)	51143	21.2	52.64	10.04	Elmhirst DF-97
6-Mar-01	J W Maeer	172(AEL)	51144	22.42	53.2	10.49	Elmhirst DF-97
6-Mar-01	J W Maeer	173(AEL)	51299	16.24	53.31	7.58	Elmhirst DF-97
6-Mar-01	J W Maeer	174(AEL)	51145	22.32	52.5	10.6	Elmhirst DF-97
6-Mar-01	J W Maeer	175(AEL)	50088	18.04	54.34	8.24	Elmhirst DF-97
6-Mar-01	J W Maeer	176(AEL)	51146	22.18	51.2	10.82	Elmhirst DF-97
7-Mar-01	J W Maeer	177(AEL)	51147	22.62	56.4	9.86	Elmhirst DF-97
9-Mar-01	J W Maeer	183(AEL)	51153	22.4	55.62	9.94	Elmhirst DF-97
9-Mar-01	J W Maeer	186(AEL)	51154	22.06	54.48	10.04	Elmhirst DF-97
9-Mar-01	J W Maeer	187(AEL)	50098	18.14	54.32	8.29	Elmhirst DF-97
9-Mar-01	J W Maeer	190(AEL)	50099	18.6	54.01	8.55	Elmhirst DF-97
12-Mar-01	J W Maeer	199(AEL)	51158	23.42	53.53	10.88	GAGG HFb-97
12-Mar-01	J W Maeer	191(AEL)	50100	16.86	52.94	7.93	Elmhirst DF-97
12-Mar-01	J W Maeer	192(AEL)	52364	15.76	54.57	7.16	Elmhirst DF-97
12-Mar-01	J W Maeer	195(AEL)	52365	15.38	51.35	7.48	Elmhirst DF-97
12-Mar-01	J W Maeer	196(AEL)	51155	21.5	50.87	10.56	Elmhirst DF-97
12-Mar-01	J W Maeer	197(AEL)	50001	17.2	52.48	8.17	Elmhirst DF-97
12-Mar-01	J W Maeer	198(AEL)	52366	15.94	52.28	7.61	Elmhirst DF-97

Delivery Date	Haulier	Weight ticket no.	Delivery ticket no.	Fresh weight (/te)	Moisture content (%)	Dry weight (/odt)	Grower
12-Mar-01	J W Maeer	200(AEL)	50003	14.96	52.77	7.07	Elmhirst DF-97
13-Mar-01	J W Maeer	202(AEL)	50004	17.04	51.23	8.31	Elmhirst DF-97
16-Mar-01	J W Maeer	218(AEL)	51166	19.16	44.55	10.62	YW AL-97
16-Mar-01	J W Maeer	219(AEL)	51168	19.32	47.63	7.27	YW AL-97
19-Mar-01	J W Maeer	221(AEL)	51161	21.3	55.53	9.47	HFa-97 Gill
19-Mar-01	J W Maeer	222(AEL)	51162	21.3	53.31	9.23	HFa-97 Gill
20-Mar-01	J W Maeer	223(AEL)	51171	19.14	45.1	6.72	YW AL-97
20-Mar-01	J W Maeer	227(AEL)	51172	21.08	51.5	8.75	HFa-97 Gill
20-Mar-01	J W Maeer	228(AEL)	51173	20.84	52.75	8.91	HFa-97 Gill
21-Mar-01	J W Maeer	229(AEL)	51175	18.62	47.68	7.02	YW AL-97
21-Mar-01	J W Maeer	230(AEL)	51176	20.52	49.15	8.03	HFa-97 Gill
21-Mar-01	J W Maeer	231(AEL)	51177	20.62	52.43	8.75	HFa-97 Gill
22-Mar-01	J W Maeer	232(AEL)	51179	17.7	47.34	6.61	YW AL-97
22-Mar-01	J W Maeer	233(AEL)	51181	18.16	45.7	6.48	YW AL-97
22-Mar-01	J W Maeer	234(AEL)	51183	17.2	45.98	6.19	YW AL-97
23-Mar-01	J W Maeer	235(AEL)	51185	18.16	48.82	7.05	YW AL-97
23-Mar-01	J W Maeer	237(AEL)	51187	17.9	44.25	6.13	YW AL-97
23-Mar-01	J W Maeer	238(AEL)	52202	13.68	51.3	6.66	Newland
28-Mar-01	J W Maeer	239(AEL)	51190	12.82	48.61	6.59	ABC
29-Mar-01	J W Maeer	240(AEL)	52214	11.1	48.51	5.72	ABC
29-Mar-01	J W Maeer	242(AEL)	52216	11.02	60.7	4.33	ABC
29-Mar-01	J W Maeer	243(AEL)	52218	11.1	58.53	4.6	ABC
30-Mar-01	J W Maeer	245(AEL)	51194	11.4	49.18	5.79	ABC
Total				**895.62**		**395.91**	

Table A18. Deliveries used to construct the forestry residue pile

Date	Haulier	Weigh ticket	7.1 Supplier	Type	Source	Fresh weight (/kg)	Moisture (%, wet basis)	Dry weight (/kg)
3/1/01	Maeers	162	A&C Chipping	Beech	Langton	22820	34.15%	15027
3/1/01	Maeers	163	A&C Chipping	Beech	Wintringham	25840	42.99%	14731
3/9/01	Bayston	184	A&C Chipping	Beech	Wintringham	15940	54.32%	7281
3/9/01	Bayston	188	A&C Chipping	Beech	Wintringham	17260	41.69%	10064
3/12/01	Bayston	194	A&C Chipping	Beech	Wintringham	17800	40.75%	10547
3/14/01	Maeers	209	A&C Chipping	Beech	Wintringham	23560	37.30%	14772
3/15/01	Maeers	215	A&C Chipping	Beech	Wintringham	23740	34.87%	15462
3/16/01	Maeers	217	A&C Chipping	Beech	Wintringham	24540	38.78%	15023
3/19/01	Maeers	220	A&C Chipping	Beech	Wintringham	25520	36.85%	16116
3/23/01	Bayston	236	A&C Chipping	Beech	Kirkburn	11340	44.67%	6274
3/29/01	Maeers	241	A&C Chipping	Beech	Wintringham	27120	34.37%	17799
3/30/01	Maeers	244	A&C Chipping	Beech	Wintringham	26440	37.60%	16499
4/6/01	Maeers	252	A&C Chipping	Beech	Wintringham	24000	42.75%	13740
4/17/01	Maeers	254	A&C Chipping		Aubourn	22520	41.50%	13174
4/17/01	Maeers	255	A&C Chipping		Aubourn	16520	46.90%	8772
4/17/01	Maeers	256	A&C Chipping		Newark	22000	32.50%	14850
4/17/01	Maeers	257	A&C Chipping		Newark	15280	32.92%	10250
4/19/01	Maeers	258	A&C Chipping		Aubourn	21500	36.77%	13594
4/20/01	Maeers	259	A&C Chipping		Aubourn	19800	37.52%	12371
4/24/01	Maeers	262	A&C Chipping		Aubourn	19080	29.89%	13377
5/30/01	Gilson	315	CH Forestry		Callans Lane	12540	44.40%	6972
5/30/01	Gilson	317	CH Forestry		Callans Lane	16900	44.40%	9396
TOTAL						**452060**		**276093**

Table A19. Total wood chip removed from the piles

Date Removed	**Weight (/gt)**	**Weight (/odt)**
24/08/2001	13.04	8.73
24/08/2001	13.22	10.13
24/08/2001	13.94	9.42
24/08/2001	15.18	11.83
28/08/2001	14.22	9.14
28/08/2001	12.86	9.75
28/08/2001	14.42	12.24
28/08/2001	15.3	11.56
29/08/2001	14.52	10.03
29/08/2001	14.82	9.87
29/08/2001	14.18	9.86
29/08/2001	13.32	9.88
29/08/2001	14.38	10.90
8 TOTAL	**183.4**	**133.34**

N.B. Precise quantities removed from SRC and FR piles undetermined.

APPENDIX 2

Table A20. Interim sampling SRC raw data

Sample Number	Sample Date	Depth (m from surface)	Time in storage (days)	Moisture (%wt)	Ash (as received)	Ash (dry basis)	DAF CV (KJ/kg)	GR CV (KJ/kg)	Particle size > 30mm	30mm> Particle size>3mm	Particle siz < <3mm
ET001D	09-Mar-01	0	0	54.0	0.60	1.32	19338	8777	2.67	93.66	3.67
ET004D	13-Mar-01	0	0	55.9	0.56	1.26	19862	8655	3.84	93.97	2.19
ET006D	20-Mar-01	0.1	8	67.8	0.46	1.43	19899	6323	2.92	92.87	4.21
ET007D	20-Mar-01	0.5	8	64.9	0.55	1.56	19929	6878	1.37	95.88	2.75
ET008D	20-Mar-01	1	8	49.5	1.24	2.46	20031	9863	0.75	92.31	6.94
ET009D	20-Mar-01	1.5	8	51.9	0.86	1.79	19881	9386	4.08	90.04	5.88
ET010D	20-Mar-01	3	8	52.0	0.63	1.31	19502	9246	1.79	93.39	4.82
ET011D	23-Mar-01	0.1	14	67.7	0.39	1.21	19953	6375	0.00	96.93	3.07
ET012D	23-Mar-01	0.5	14	55.3	0.51	1.15	19645	8681	0.00	95.92	4.08
ET013D	23-Mar-01	1	14	56.1	0.73	1.65	20233	8739	0.00	95.50	4.50
ET014D	23-Mar-01	1.5	14	53.0	0.73	1.56	20002	9262	0.00	93.64	6.36
ET015D	23-Mar-01	3	14	50.8	0.72	1.46	19811	9610	0.00	90.06	9.94
ET021D	30-Mar-01	0.1	23	48.8	0.63	1.23	19625	9934	0.00	93.81	6.19
ET022D	30-Mar-01	0.5	23	69.4	0.80	2.63	19676	5855	0.00	92.93	7.07
ET023D	30-Mar-01	1	23	51.2	0.73	1.50	19793	9523	0.00	94.14	5.86
ET024D	30-Mar-01	1.5	23	52.5	0.78	1.64	20062	9381	0.00	94.47	5.53
ET025D	30-Mar-01	3	23	43.4	0.85	1.51	19379	10798	3.37	93.74	2.89
ET033D	25-May-01	0.1	57	50.6	1.89	3.82	20102	9555	0.00	100.00	0.00
ET034D	25-May-01	0.5	57	55.9	0.95	2.16	19774	8530	0.00	100.00	0.00
ET035D	25-May-01	1	57	46.6	1.33	2.49	19823	10316	0.00	100.00	0.00
ET036D	25-May-01	1.5	57	45.4	0.90	1.65	19622	10529	0.00	100.00	0.00

Sample Number	Sample Date	Depth (m from surface)	Time in storage (days)	Moisture (%wt)	Ash (as received)	Ash (dry basis)	DAF CV (KJ/kg)	GR CV (KJ/kg)	Particle size > 30mm	30mm> Particle size>3mm	Particle siz < <3mm
ET037D	25-May-01	3	57	40.3	1.44	2.42	19185	11186	0.00	100.00	0.00
ET043D	21-Jun-01	0.1	84	41.4	1.02	1.74	19697	11341	0.00	95.56	4.44
ET044D	21-Jun-01	0.5	84	39.0	2.05	3.36	18957	11182	0.00	93.04	6.96
ET045D	21-Jun-01	1	84	47.5	1.25	2.38	19385	9940	0.00	91.77	8.23
ET046D	21-Jun-01	1.5	84	45.8	1.86	3.43	19212	10055	0.00	89.78	10.22
ET047D	21-Jun-01	3	84	27.5	0.95	1.30	19710	14103	0.00	95.83	4.17
ET061D	13-Aug-01	0.1	176	69.72	0.36	1.20	20054	5999	0.82	94.89	4.29
ET062D	13-Aug-01	0.5	176	36.7	1.28	2.02	20291	12585	2.89	93.49	3.61
ET063D	13-Aug-01	1	176	51.11	0.85	1.74	20190	9699	4.37	90.09	5.54
ET064D	13-Aug-01	1.5	176	30.7	0.89	1.29	20051	13716	3.22	92.6	4.18
ET065D	13-Aug-01	3	176	28.9	0.91	1.28	19933	13991	1.94	91.97	6.09
ET076D	07-Jan-02	0.1	308	71.59	0.31	1.09	20071	5640			
ET077D	07-Jan-02	0.5	308	71.2	0.39	1.37	20042	5693			
ET078D	07-Jan-02	1	308	0	2.22	2.22	20167	19719			
ET079D	07-Jan-02	1.5	308	40.16	0.79	1.33	20030	11827			
ET080D	07-Jan-02	3	308	60.96	0.58	1.48	20090	7727			
ET086D	03-Apr-02	0.1	346	68.41	0.44	1.38	20313	6328			
ET087D	03-Apr-02	0.5	346	65.75	0.74	2.15	20433	6847			
ET088D	03-Apr-02	1	346	69.09	0.61	1.98	20196	6119			
ET089D	03-Apr-02	1.5	346	45.64	1.69	3.11	20029	10550			
ET090D	03-Apr-02	3	346	37.84	5.04	8.11	20903	11939			
ET091D	05-Jun-02	0.1	461	68.45	0.57	1.81	20190	6255	0.39	93.54	6.06
ET092D	05-Jun-02	0.5	461	18.83	1.38	1.70	20277	16179	0.77	91.43	7.8
ET093D	05-Jun-02	1	461	41.16	1.23	2.09	20437	11774	0.58	92.95	0.69
ET094D	05-Jun-02	1.5	461	35.38	5.55	8.59	20801	12286	0.15	81.9	18
ET095D	05-Jun-02	3	461	30.8	2.03	2.93	20454	13740	0.45	91.15	8.4

Table A21. Interim sampling forestry residue raw data

Sample Number	Sample Date	Depth (m from surface)	Time in storage (days)	Moisture (%wt)	Ash (as received)	Ash (dry basis)	DAF CV (KJ/kg)	GR CV (KJ/kg)	Particle size > 30mm	30mm> Particle size>3mm	Particle size < 3mm
ET005D	20-Mar-01	0	0	38.1	0.93	1.51	19667	12000	8.64	83.87	7.49
ET016D	23-Mar-01	0.1	8	47.1	0.73	1.39	19803	10338	6.28	85.39	8.33
ET017D	23-Mar-01	0.5	8	52.3	0.79	1.65	20069	9423	0.00	87.41	12.59
ET018D	23-Mar-01	1	8	41.0	0.82	1.40	19944	11607	5.07	85.16	9.77
ET019D	23-Mar-01	1.5	8	40.3	1.78	2.97	19467	11282	3.56	83.37	13.07
ET020D	23-Mar-01	3	8	38.8	1.09	1.78	19842	11931	0.00	85.34	14.66
ET026D	30-Mar-01	0.1	15	57.6	0.79	1.87	19533	8131	7.45	81.31	11.24
ET027D	30-Mar-01	0.5	15	47.8	1.34	2.56	19936	10150	4.83	84.78	10.39
ET028D	30-Mar-01	1	15	38.2	1.08	1.75	19650	11927	3.59	83.62	12.79
ET029D	30-Mar-01	1.5	15	35.3	1.26	1.94	19889	12610	4.33	85.06	10.61
ET030D	30-Mar-01	3	15	36.1	1.08	1.69	19592	12318	4.46	84.39	11.15
ET031D	30-Mar-01	0	0	36.3	0.47	0.74	19101	12086	15.25	82.02	2.73
ET032D	19-Apr-01	0	0	39.5	0.00	0.00	0	0	0.00	100.00	0.00
ET038D	25-May-01	0.1	35	48.4	1.19	2.31	19872	10019	0.00	100.00	0.00
ET039D	25-May-01	0.5	35	42.4	1.92	3.33	19999	11137	0.00	100.00	0.00
ET040D	25-May-01	1	35	28.3	2.16	3.01	19323	13446	0.00	100.00	0.00
ET041D	25-May-01	1.5	35	26.0	3.13	4.23	19535	13837	0.00	100.00	0.00
ET042D	25-May-01	3	35	29.8	1.53	2.17	19276	13244	0.00	100.00	0.00
ET048D	21-Jun-01	0.1	64	33.6	0.88	1.33	19598	12850	0.00	89.38	10.62
ET049D	21-Jun-01	0.5	64	50.4	0.53	1.06	19695	9665	13.32	76.06	10.62
ET050D	21-Jun-01	1	64	27.3	1.21	1.66	19295	13795	9.60	80.44	9.96
ET051D	21-Jun-01	1.5	64	28.6	1.21	1.69	19413	13619	11.06	81.71	7.23
ET052D	21-Jun-01	3	64	26.0	1.16	1.57	19492	14198	8.67	84.18	7.15

Sample Number	Sample Date	Depth (m from surface)	Time in storage (days)	Moisture (%wt)	Ash (as received)	Ash (dry basis)	DAF CV (KJ/kg)	GR CV (KJ/kg)	Particle size > 30mm	30mm> Particle size>3mm	Particle size < 3mm
ET053D	12-Jul-01	0.1	117	50.67	0.80	1.62	19484	9456	0.001	97.6	2.4
ET054D	12-Jul-01	0.5	117	55.22	0.41	0.92	19423	8618	0.001	98.48	1.52
ET055D	12-Jul-01	1	117	35.16	1.10	1.69	19716	12567	0.001	98.41	1.59
ET056D	12-Jul-01	1.5	117	31.25	2.04	2.96	20030	13363	0.32	98.54	1.14
ET057D	12-Jul-01	3	117	28.64	1.78	2.50	19990	13908	0.001	98.19	1.81
ET066D	01-Nov-01	0.1	216	51.82	0.72	1.49	19825	9409			
ET067D	01-Nov-01	0.5	216	59.18	1.26	3.09	19821	7841			
ET068D	01-Nov-01	1	216	43.61	1.12	1.99	19722	10899			
ET069D	01-Nov-01	1.5	216	25.75	1.05	1.42	18698	13686			
ET070D	01-Nov-01	3	216	27.03	0.82	1.13	19067	13756			
ET071D	07-Jan-02	0.1	277	61.16	1.78	4.58	20693	7669			
ET072D	07-Jan-02	0.5	277	32.33	2.46	3.64	20568	13412			
ET073D	07-Jan-02	1	277	56.69	0.93	2.15	19911	8438			
ET074D	07-Jan-02	1.5	277	26.3	3.98	5.40	19491	13588			
ET075D	07-Jan-02	3	277	38.03	1.11	1.79	19933	12131			
ET081D	21-Feb-02	0.1	345	63.81	0.46	1.27	20278	7246			
ET082D	21-Feb-02	0.5	345	62.92	0.63	1.70	19908	7256			
ET083D	21-Feb-02	1	345	33.54	1.08	1.62	19980	13063			
ET084D	21-Feb-02	1.5	345	36	1.55	2.42	20060	12528			
ET085D	21-Feb-02	3	345	26.69	1.53	2.08	20030	14378			
ET096D	05-Jun-02	0.1	453	60.81	1.47	3.74	20215	7626	0.76	80.09	11.48
ET097D	05-Jun-02	0.5	453	62.26	1.65	4.38	20442	7376	5.2	84.8	9.97
ET098D	05-Jun-02	1	453	37.78	1.44	2.32	19977	12141	11.72	77.55	10.74
ET099D	05-Jun-02	1.5	453	32.04	2.29	3.36	19771	12985	7.76	80.88	11.36
ET100D	05-Jun-02	3	453	25.96	1.59	2.15	20031	14511	1.06	79.84	9.7

APPENDIX 3

Table A22. SRC thermocouple and local weather data

Date	Time	Rain	Thermometer readings (°C)			Thermocouple readings (°C)											
		(/mm)	Max	Min	Ambient	1	2	3	4	5	6	7	8	9	10	11	12
08-Mar-01	16:20					42.7	31.9	27.3	18.3	17.7	15.0	11.9	44.8	11.6	13.0	37.1	13.8
09-Mar-01	15:00					66.5	57.0	42.6	36.5	25.0	19.9	13.0	44.9	17.8	13.8	60.0	20.8
14-Mar-01	17:00					69.3	60.0	60.2	63.7	45.8	55.1	44.3	60.2	60.5	50.6	64.0	55.8
16-Mar-01	9:30					43.0	61.0	66.0	66.0	63.0	63.0	20.0	55.0	64.0	50.0	62.0	55.0
20-Mar-01	8:45					16.1	63.0	64.4	64.7	56.3	58.4	5.8	45.1	59.5	57.9	64.1	56.3
21-Mar-01	9:00		10.0	0.0		11.1	58.0	53.1	48.3	61.9	58.7	6.7	29.9	57.8	15.5	44.8	44.3
23-Mar-01	10:00		8.0	0.0	8.0	12.3	57.3	55.7	58.8	62.8	59.5	8.3	37.8	57.5	27.6	40.7	42.0
30-Mar-01	8:45		13.0	2.0	7.0	30.6	52.6	56.5	53.0	51.6	57.0	14.6	55.3	51.6	7.7	20.7	9.2
11-Apr-01	17:00		21.0	1.0	11.0	49.8	15.3	8.5	10.6	22.9	38.2	26.7	20.6	54.5	12.8	20.2	38.8
18-Apr-01	9:30		21.0	-1.0	9.0	27.9	9.7	7.0	7.4	24.6	36.7	55.1	13.6	53.1	41.2	37.8	31.2
20-Apr-01	16:00		16.0	0.0	16.0	17.1	6.5	5.1	6.0	19.7	42.9	48.8	11.5	49.9	38.0	42.9	30.1
04-May-01		17	26.0	-1.0	11.0	22.9	46.9	30.9	24.8	33.3	33.2	44.7	34.3	53.1	27.2	38.6	30.7
25-May-01	11:00	15	33.0	-1.0	14.0	35.2	45.0	45.0	48.5	35.0	32.9	30.2	34.5	41.9	32.9	33.4	22.5
01-Jun-01	14:00	2	31.0	8.0	17.0	45.0	13.6	13.5	15.3	16.5	17.4	26.0	24.2	38.0	25.5	35.0	23.2
11-Jun-01	13:00	4	26.0	3.0	16.0	29.1	9.0	16.4	10.3	11.2	21.1	26.5	13.7	15.6	24.4	33.8	17.3
21-Jun-01	14:00	28	26.0	3.0	20.0	29.5	13.8	16.1	16.5	16.2	19.0	34.8	28.8	31.0	31.4	34.5	27.1
25-Jun-01	16:00	0	37.0	16.0	32.0	35.0	16.5	20.5	22.7	19.5	24.5	35.2	26.2	38.7	39.2	26.9	19.5
02-Jul-01	14:00	0	49.0	30.0	37.0	34.5	32.0	29.6	31.8	25.4	32.5	34.0	39.9	36.0	39.4	35.6	24.8
05-Jul-01	13:00	0	32.0	11.0	30.0	28.9	37.2	38.9	37.5	36.5	34.0	26.7	32.6	29.4	33.8	28.4	25.6
09-Jul-01	12:30	2	34.0	10.0	22.0	32.4	27.0	28.2	32.4	31.1	34.1	27.1	41.4	35.8	41.0	34.0	25.5
12-Jul-01	9:00	6	27.0	10.0	14.0	35.2	15.9	14.3	14.3	14.4	22.6	29.3	22.7	28.3	17.8	30.1	16.9

Date	Time	Rain	Thermometer readings (^{o}C)			Thermocouple readings (^{o}C)											
		(/mm)	Max	Min	Ambient	1	2	3	4	5	6	7	8	9	10	11	12
16-Jul-01	12:15	0	29.0	4.0	26.0	28.7	15.2	14.9	15.7	16.0	18.8	28.5	17.6	26.7	30.3	30.6	22.8
23-Jul-01	10:30	1	28.0	7.0	25.0	18.4	25.6	23.7	24.8	33.5	30.3	23.3	22.7	24.3	27.4	21.1	20.3
26-Jul-01	9:00	0	30.0	12.0	22.0	26.0	29.1	27.6	30.8	33.2	29.4	27.1	25.2	23.1	39.1	24.0	31.3
30-Jul-01	9:00	0	40.0	10.0	26.0	27.9	29.2	33.1	35.8	36.2	33.2	37.0	34.8	24.8	42.5	32.7	33.5
03-Aug-01	15:45	0	33.0	10.0	22.0	31.5	32.8	35.7	34.5	29.3	26.0	23.3	37.6	31.3	22.9	26.5	19.1
07-Aug-01	11:30	20	28.0	8.0	14.0	32.8	36.9	36.2	36.2	31.1	31.9	20.4	35.2	32.5	36.8	24.7	24.8
09-Aug-01	9:00	26	18.0	12.0	17.0	29.3	26.4	23.0	25.4	22.5	27.0	19.0	35.4	31.3	21.6	26.0	22.2
13-Aug-01	10:00	5	26.0	7.0	22.0	34.0	21.0	17.5	17.2	19.4	23.9	25.5	32.4	31.6	22.6	26.3	23.1
17-Aug-01	13:45	10	35.0	9.0	22.0	34.3	23.4	26.9	25.5	20.7	22.2	29.3	27.8	31.6	40.3	30.9	31.1
21-Aug-01	10:30	15	27.0	9.0	23.0	28.5	33.2	31.8	30.0	27.1	26.8	22.0	33.4	31.1	27.3	24.0	28.1
24-Aug-01	16:30	0	30.0	14.0	20.0	24.9	29.7	30.2	31.9	30.8	29.9	26.0	27.7	26.3	31.7	26.3	30.1
28-Aug-01	15:00	0	35.0	6.0	29.0	36.2	39.2	40.2	39.0	35.8	31.2	25.4	33.8	31.0	31.3	32.0	25.8
30-Aug-01	15:30	1	35.0	6.0	17.0	37.2	35.8	37.2	36.0	34.1	30.2	34.1	35.3	30.9	23.5	26.2	21.0
14-Sep-01	9:30	10	20.0	2.0	14.0	24.5	10.7	10.3	10.4	14.5	18.7	18.5	16.4	22.3	17.5	22.5	17.6
17-Sep-01	9:10	5	29.0	4.0	14.0	21.9	11.2	10.4	10.5	12.4	15.2	14.2	13.6	22.6	13.4	22.9	17.0
28-Sep-01	9:45	28	25.0	12.0	16.0	17.2	22.4	24.6	24.4	18.0	19.8	17.6	21.0	23.9	20.3	20.3	21.2
03-Oct-01	16:00	7	26.0	12.0	18.0	16.0	24.3	23.9	24.9	27.9	26.8	13.5	22.1	25.2	15.2	19.5	18.8
08-Oct-01	14:00	10	26.0	11.0	16.0	10.1	15.4	14.7	16.0	16.5	19.6	10.4	14.1	17.6	10.7	14.1	12.9
11-Oct-01	16:30	1.5	27.0	10.0	20.0	15.1	25.9	19.9	19.4	22.8	25.6	14.1	18.3	21.6	16.0	15.1	17.8
15-Oct-01	13:00	0.5	23.0	12.0	18.0	22.7	16.5	16.4	17.2	19.2	22.0	26.7	16.7	19.8	20.6	19.4	22.5
19-Oct-01	10:40	7	21.0	5.0	11.0	14.3	22.4	22.0	24.1	21.7	24.0	14.8	18.4	19.7	15.7	13.8	15.1

Date	Time	Rain	Thermometer readings (^{o}C)			Thermocouple readings (^{o}C)											
		(/mm)	Max	Min	Ambient	1	2	3	4	5	6	7	8	9	10	11	12
22-Oct-01	15:00	23	20.0	10.0	15.0	17.4	21.4	23.7	23.6	21.0	21.3	17.9	17.8	17.7	19.0	16.7	18.3
30-Oct-01	13:40	23	21.0	5.0	20.0	21.2	26.5	23.4	24.4	24.3	25.6	14.4	23.9	25.6	15.4	21.0	16.3
01-Nov-01	11:00	0	18.0	4.0	15.0	24.2	11.0	11.6	12.1	12.4	18.8	17.4	18.4	25.9	12.1	21.8	19.9
06-Nov-01	10:25	0	16.0	1.0	12.0	21.4	9.6	9.8	9.5	9.8		17.1	9.1		18.5		
12-Nov-01	13:15	12	16.0	4.0	16.0	19.4	4.1	3.2	4.8	8.7	12.0	12.0	10.1	17.4	7.5	19.5	6.4
20-Nov-01	9:25	1	15.0	2.0	8.0	18.4	8.6	7.9	7.6	6.7	10.8	13.0	10.6	18.2	16.2	13.5	11.6
10-Dec-01	10:12	14	16.0	1.0	5.0	7.5	11.6	13.9	14.5	12.6	15.1	8.0	9.2	10.2	8.2	8.9	9.0
17-Dec-01	9:30	2	14.0	2.0	13.0	8.3	17.3	22.0	20.5	19.1	17.8	7.4	9.4	14.8	10.4	12.7	11.2
07-Jan-02	10:25	5	8.0	-9.0	6.0	1.6	12.3	13.6	13.8	15.5	16.0	0.6	4.8	6.9	0.8	1.6	1.4
21-Jan-02	15:30	5	15.0	-2.0	13.0	6.9	9.9	12.6	12.9	8.6	8.1	7.8	6.7	11.7	11.0	10.4	7.9
08-Feb-02	11:10	22	16.0	3.0	10.0	11.2	9.0	5.7	6.4	9.3	14.3	8.1	13.5	14.7	5.9	10.6	7.7
18-Feb-02	16:00	9	18.0	-2.0	14.0	12.3	6.5	5.0	5.2	8.0	11.9	11.8	8.3	14.3	14.9	14.0	9.5
21-Feb-02	10:15	6	10.0	0.0	4.0	11.4	5.6	5.2	5.4	6.1	6.0	8.3	4.4	11.1	6.9	15.3	9.0
01-Mar-02	16:00	15	15.0	1.0	5.0	7.6	5.3	6.1	6.4	6.0	8.1	8.6	7.6	11.3	7.0	11.3	9.2
04-Mar-02	16:00	2	15.0	-2.0	10.0	8.1	4.1	2.9	3.9	6.2	11.7	8.2	4.6	9.5	8.6	11.6	9.9
08-Mar-02	16:10	0	16.0	0.0	12.0	6.9	7.3	6.5	7.1	8.8	8.4	9.8	7.1	10.5	10.9	14.5	11.0
15-Mar-02	10:20	8	18.0	3.0	5.0	3.5	10.0	9.1	9.8	11.5	11.0	2.6	5.2	7.4	2.5	4.1	3.1
28-Mar-02	15:20	12	22.0	1.0	16.0	14.6	10.1	10.4	9.0	7.0	9.8	15.5	14.6	12.6	14.7	12.4	15.1
09-Apr-02	13:20	0	27.0	4.0	15.0	10.7	17.0	18.2	16.4	16.6	16.5	8.5	17.2	15.0	10.3	9.3	9.5
26-Apr-02	10:15	3	32.0	2.0	11.0	16.1	14.4	14.1	12.6	12.3	14.0	21.9	14.2	16.3	25.9	14.9	19.5
10-May-02	10:00	10	25.0	2.0	15.0	14.6	8.8	8.0	7.8	10.4	13.2	14.4	9.8	13.4	14.9	15.3	7.2

Table A23. Forestry residue thermocouple and local weather data

		Rain	Thermometer readings (^{o}C)			Thermocouple readings (^{o}C)											
Date	Time	(/mm)	Max	Min	Ambient	1	2	3	4	5	6	7	8	9	10	11	12
21-Mar-01	9:00		10.0	0.0			58.9	48.2	38.0	43.7	39.5	32.5	29.3	32.3	24.6	35.8	10.9
23-Mar-01	10:30		8.0	0.0	8.0		69.4	69.1	69.0	64.2	64.4	58.5	68.0	61.0	45.8	40.6	17.7
30-Mar-01	8:45		13.0	2.0	7.0	66.3	67.1	66.8	63.8	60.7	57.9	61.3	63.6	57.9	61.4	55.4	31.1
11-Apr-01	17:00		21.0	1.0	11.0	50.0	59.5	59.0	58.1	58.1	52.8	60.0	57.9	55.1	47.8	49.9	21.8
18-Apr-01	9:30		21.0	-1.0	9.0	35.7	55.2	57.3	46.2	56.4	52.6	58.9	57.5	52.7	36.0	31.7	19.9
20-Apr-01	16:00		16.0	0.0	16.0	44.3	55.0	56.7	33.2	47.8	44.9	57.3	56.5	51.9	46.2	33.0	19.3
4-May-01		17	26.0	-1.0	11.0	19.9	54.1	50.0	30.7	40.7	37.7	22.3	43.2	32.3	36.5	31.2	25.8
25-May-01	11:00	15	33.0	-1.0	14.0	23.4	45.4	44.0	40.4	52.8	42.9	37.1	40.9	34.7	29.5	29.2	32.8
1-Jun-01	14:00	2	31.0	8.0	17.0	19.9	31.2	36.3	29.8	51.7	39.3	36.7	36.9	36.1	37.6	32.0	21.4
11-Jun-01	13:00	4	26.0	3.0	16.0	12.6	14.6	18.1	16.6	21.6	26.0	22.2	21.8	28.0	31.5	30.7	20.4
21-Jun-01	14:00	28	26.0	3.0	20.0	16.6	14.1	16.6	20.6	22.8	28.4	20.5	20.9	27.6	32.0	32.2	23.0
25-Jun-01	16:00	0	37.0	16.0	32.0	18.5	16.1	18.1	23.8	24.2	28.6	23.1	22.9	29.7	33.8	32.0	31.4
2-Jul-01	14:00	0	49.0	30.0	37.0	38.7	25.6	22.5	40.1	34.0	34.6	31.5	29.0	32.4	35.3	33.4	27.5
5-Jul-01	13:00	0	32.0	30.0	30.0	20.6	28.1	29.3	38.3	28.2	30.6	33.6	35.2	33.7	31.6	32.0	29.1
9-Jul-01	12:30	2	34.0	10.0	22.0	32.2	44.7	43.0	37.1	38.4	36.3	39.9	40.1	34.6	34.1	32.8	23.9
12-Jul-01	9:00	6	27.0	10.0	14.0	23.9	35.1	36.2	30.2	35.3	34.2	38.0	37.5	35.1	29.3	27.0	18.7
16-Jul-01	12:15	0	29.0	4.0	26.0	18.6	25.4	31.0	28.2	31.6	32.8	35.1	34.9	35.7	29.0	26.6	22.5
23-Jul-01	10:30	1	28.0	7.0	25.0	31.4	25.3	29.7	23.2	27.5	29.8	33.6	34.4	34.0	26.4	27.5	27.6
26-Jul-01	9:00	0	30.0	12.0	22.0	30.8	24.7	29.8	21.9	26.6	29.2	33.9	33.9	34.0	26.7	28.8	29.4
30-Jul-01	9:00	0	40.0	10.0	26.0	24.3	22.0	26.4	19.9	23.1	26.6	33.7	29.4	31.3	31.2	31.0	28.7
3-Aug-01	15:45	0	33.0	10.0	22.0	16.1	25.3	26.8	20.7	24.6	27.3	32.9	30.4	32.1	31.7	31.8	29.3

Date	Time	Rain	Thermometer readings (^{o}C)			Thermocouple readings (^{o}C)											
		(/mm)	Max	Min	Ambient	1	2	3	4	5	6	7	8	9	10	11	12
9-Aug-01	9:00	26	18.0	12.0	17.0	31.8	28.5	24.6	26.0	27.8	29.0	31.9	27.7	30.6	30.6	30.1	24.1
13-Aug-01	10:00	5	26.0	7.0	22.0	21.2	30.0	28.6	26.0	30.5	29.9	32.4	30.3	32.0	28.6	28.1	23.7
17-Aug-01	13:45	10	35.0	9.0	22.0	28.2	31.3	31.8	26.0	30.2	30.0	33.0	33.2	32.9	27.6	27.7	28.5
21-Aug-01	10:30	15	27.0	9.0	23.0	30.0	33.3	34.1	26.8	31.0	31.1	31.6	34.3	23.7	29.7	29.5	29.3
24-Aug-01	16:30	0	30.0	14.0	0.0	19.5	33.9	33.6	31.5	33.5	33.7	26.9	32.0	31.1	28.8	29.3	28.1
28-Aug-01	15:00	0	35.0	6.0	29.0	34.3	35.9	36.2	29.5	33.3	33.4	30.1	35.0	34.0	29.9	30.9	30.8
30-Aug-01	15:30	1	35.0	6.0	17.0	27.3	36.4	36.3	30.4	34.0	33.9	30.1	34.8	33.0	31.6	30.2	29.0
3-Sep-01	14:15	0	26.0	9.0	22.0	23.5	33.5	33.5	26.9	29.7	29.4	35.4	32.7	34.0	33.2	31.5	23.0
14-Sep-01	9:30	10	20.0	2.0	14.0	11.0	13.1	14.8	14.9	16.2		17.2	16.1	21.6	21.9	27.6	23.4
17-Sep-01	9:10	5	29.0	4.0	11.0	11.3	11.8	13.5	12.2	15.9	19.7	15.4	15.5	22.5	19.3	26.9	29.1
28-Sep-01	9:45	28	25.0	12.0	16.0	13.7	12.3	13.2	13.4	16.4	20.9	14.9	15.3	22.7	19.3	26.4	26.8
3-Oct-01	16:00	7	26.0	12.0	18.0	14.7	18.9	21.7	19.8	23.6	27.1	17.9	26.8	31.7	18.7	28.4	26.3
8-Oct-01	14:00	10	26.0	11.0	16.0	10.6	14.0	14.5	21.2	21.4	26.7	13.4	15.5	21.5	13.5	17.7	16.1
11-Oct-01	16:30	1.5	27.0	10.0	20.0	14.5	17.8	15.9	30.9	30.4		14.2	17.3	26.0	14.0	21.3	23.0
15-Oct-01	13:00	0.5	23.0	12.0	18.0	14.1	15.5	15.6	25.4	24.7		16.1	16.3	24.6	15.2	22.8	22.4
19-Oct-01	10:40	7	21.0	5.0	11.0	12.6	16.4	16.1	21.2	20.7		15.6	16.6	24.7	16.2	22.5	20.4
22-Oct-01	15:00	23	20.0	10.0	15.0	13.6	18.0	16.3	29.9	29.9		16.4	17.8	21.1	16.7	24.4	23.0
30-Oct-01	13:40	23	21.0	5.0	20.0	14.7	21.0	20.1	33.4	33.5		20.3	21.7	30.2	33.7	32.3	23.4
1-Nov-01	11:00	0	18.0	4.0	15.0	23.9	27.2	30.7	25.4	28.0		26.7	32.4	25.3	30.0	35.3	20.9
6-Nov-01	10:25	0	16.0	1.0	12.0	11.2	15.8	22.4	23.6	24.2		27.6	29.2	33.6	30.7	28.9	19.7

Date	Time	Rain	Thermometer readings (^{o}C)			Thermocouple readings (^{o}C)											
		(/mm)	Max	Min	Ambient	1	2	3	4	5	6	7	8	9	10	11	12
12-Nov-01	13:15	12	16.0	4.0	16.0	4.7	7.5	11.9	15.0	23.3		15.3	19.8	32.3	32.9	36.1	19.3
20-Nov-01	9:25	1	15.0	2.0	8.0	6.3	6.2	9.4	13.8	22.7		14.4	18.2	33.6	30.2	28.8	19.3
10-Dec-01	11:10	14	16.0	1.0	5.0	5.2	18.5	16.9	30.0	23.6		8.7	14.5	20.8	8.3	24.4	20.7
17-Dec-01	9:15	2	2.0	14.0	13.0	8.0	23.4	18.7	28.4	25.4		9.2	13.3	21.3	8.3	30.0	24.2
7-Jan-02	10:25	5	8.0	-9.0	6.0	0.2	9.2	12.1	9.8	24.6		15.1	23.3	27.0	9.3	13.6	9.1
21-Jan-02	15:30	5	15.0	-2.0	13.0	8.5	17.0	9.4	28.8	17.1		5.3	6.8	16.7	6.8	18.9	23.8
8-Feb-02	11:10	22	16.0	3.0	10.0	7.3	16.0	22.4	14.1	27.4		17.0	25.3	30.0	11.6	20.4	19.1
18-Feb-02	16:00	9	18.0	-2.0	14.0	6.9	8.8	10.9	11.1	21.6		20.6	21.0	32.7	20.0	24.3	20.9
21-Feb-02	10:15	6	10.0	0.0	4.0	5.9	5.4	8.1	16.4	21.1		9.0	14.1	26.9	24.2	32.9	16.1
1-Mar-02	16:00	15	15.0	1.0	5.0	5.4	5.6	8.5	10.5	21.6		18.2	18.5	32.9	15.4	19.7	13.6
4-Mar-02	16:00	2	15.0	-2.0	10.0	4.2	5.3	7.8	10.1	21.1		14.6	18.1	33.0	18.7	21.8	18.0
8-Mar-02	16:10	0	16.0	0.0	12.0	7.7	6.4	6.0	9.6	14.8		7.2	15.0	24.2	26.1	31.0	17.0
15-Mar-02	10:20	8	18.0	3.0	5.0	3.6	9.4	11.4	25.5	25.2		5.6	17.3	21.6	9.0	18.9	15.0
28-Mar-02	15:20	12	22.0	1.0	16.0	9.5	12.8	12.4	27.7	19.0		9.4	11.8	22.5	11.6	22.7	18.9
9-Apr-02	13:20	0	27.0	4.0	15.0	8.1	13.9	13.3	14.8	21.1		12.5	14.0	28.3	13.7	31.2	28.2
26-Apr-02	10:15	3	32.0	2.0	11.0	18.4	27.1	27.8	18.5	24.7		22.3	30.8	36.4	22.4	27.9	27.6
10-May-02	10:00	10	25.0	2.0	15.0	19.2	12.4	17.6	12.5	16.8		24.4	21.9	29.9	24.9	30.7	23.2
17-May-02	16:00	3	7.0	35.0	19.0	16.1	22.2	24.8	26.9	33.6		17.2	27.3	31.4	18.3	27.6	22.5

APPENDIX 4

Table A24. Biochemical analysis of SRC interim samples

Sample ID	Depth (m from surface)	Time in storage (days)	Oven Dry matter %	Cellulose %	W/S Carbohydrates%	Total Ash %	Ethanol mg/kg	Acetic acid mg/kg	Propionic acid mg/kg	iso-Butyric acid mg/kg	n-Butyric acid mg/kg	iso-Valeric acid mg/kg	n-Valeric acid mg/kg	iso-Caproic acid mg/kg	n-Caproic acid mg/kg	Lactic acid mg/kg
ET001A	0.0	0	48.6	52.4	2.23	1.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	9376
ET002A	0.0	0	48.6	53.4	1.81	1.7	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	4921
ET004A	0.0	0	53.9	53.8	1.79	1.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	3025
ET006A	0.1	8	36.9	63.9	0.9	2.4	< 325	439	< 325	< 325	< 325	< 325	< 325	< 325	< 325	1317
ET007A	0.5	8	38.2	67.1	0.9	1.9	< 325	649	< 325	< 325	< 325	< 325	< 325	< 325	< 325	1299
ET008A	1.0	8	53.3	70.1	0.9	2.2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	2804
ET009A	1.5	8	48.5	67.6	1.8	2	< 325	497	< 325	< 325	< 325	< 325	< 325	< 325	< 325	1507
ET010A	3.0	8	49.8	63	0.45	1.6	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET011A	0.1	14	36.6	62.9	0.9	1.3	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	992
ET012A	0.5	14	45.9	62.8	1.78	1.7	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	1045
ET013A	1.0	14	49.8	62.1	1.34	1.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET014A	1.5	14	51.3	64.9	1.12	1.5	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET015A	3.0	14	49.7	63.4	1.48	1.4	< 325	336	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET021A	0.1	23	31	68.7	0.31	1.7	< 325	< 325	1000	< 325	< 325	< 325	< 325	< 325	< 325	2583
ET022A	0.5	23	34.2	64.2	0.31	2.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET023A	1.0	23	51	66.9	0.61	1.6	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	815
ET024A	1.5	23	47.9	62.8	1.22	1.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	1668
ET025A	3.0	23	57.9	65.1	0.3	1.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET033A	0.1	57	41.5	67.2	1.1	5.5	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800

Sample ID	Depth (m from surface)	Time in storage (days)	Oven Dry matter %	Cellulose %	W/S Carbohydrates%	Total Ash %	Ethanol mg/kg	Acetic acid mg/kg	Propionic acid mg/kg	iso-Butyric acid mg/kg	n-Butyric acid mg/kg	iso-Valeric acid mg/kg	n-Valeric acid mg/kg	iso-Caproic acid mg/kg	n-Caproic acid mg/kg	Lactic acid mg/kg
ET034A	0.5	57	47.1	64.9	0.37	4.7	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET035A	1	57	61.1	43.1	0.36	3.4	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET036A	1.5	57	60.6	67.5	0.36	2.8	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET037A	3	57	65.7	70.3	0.37	2.7	<325	455	<325	<325	<325	<325	<325	<325	<325	<800
ET043A	0.1	84	60.3	71.5	0.38	3.1	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET044A	0.5	84	64.2	66.1	0.38	4.5	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET045A	1	84	59	66.4	0.38	5.5	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET046A	1.5	84	55.8	67	0.38	12.3	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET047A	3	84	62.4	67.4	0.38	3.8	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET058A	0.5	Composite	25.8	72.6	1.2	4.3	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET059A	0.5	Composite	25.6	58.3	1.6	4.1	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET061A	0.1	176	31.1	76.8	0.1	1.3	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET062A	0.5	176	78	70	0.1	1.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET063A	1	176	49.6	70.5	0.1	1.8	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET064A	1.5	176	72.1	75.8	0.1	1.5	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET065A	3	176	75.6	72.9	0.1	1.2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET076A	0.1	308	27.1	70	0.41	1.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET077A	0.5	308	29.1	73.1	0.41	1.3	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET078A	1	308	28.5	71.3	0.41	1.5	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET079A	1.5	308	51.3	72	0.41	1.3	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET080A	3	308	64.3	69.4	0.41	1	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET086A	0.1	346	28.3	70.9	0.1	0.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET087A	0.5	346	28.6	61.6	0.1	1	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET088A	1	346	29.4	69.4	0.1	1.7	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET089A	1.5	346	55.5	66	0.1	2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET090A	3	346	65.8	63	0.1	5.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800

Table A25. Biochemical analysis of forestry residue interim samples

Sample ID	Depth (m from surface)	Time in storage (days)	Oven Dry matter %	Cellulose %	W/S Carbohydrates%	Total Ash %	Ethanol mg/kg	Acetic acid mg/kg	Propionic acid mg/kg	iso-Butyric acid mg/kg	n-Butyric acid mg/kg	iso-Valeric acid mg/kg	n-Valeric acid mg/kg	iso-Capr-oic acid mg/kg	n-Capr-oic acid mg/kg	Lactic acid mg/kg
ET003A	0.0	0	64.1	53.9	0.45	1.6	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	2047
ET005A	0.0	0	63.8	69.8	0.9	2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	1126
ET016A	0.1	8	55.5	62.9	0.37	1.9	< 325	349	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET017A	0.5	8	53.7	63	0.37	2.2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	1497
ET018A	1.0	8	62.5	64.3	0.37	1.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET019A	1.5	8	63.6	61.3	0.37	3.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET020A	3.0	8	63.4	65.2	0.37	2.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET026A	0.1	15	47.5	65.3	0.1	1.6	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	1790
ET027A	0.5	15	60.5	64.6	0.1	1.5	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	1381
ET028A	1.0	15	63.5	63.9	0.1	2.1	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	955
ET029A	1.5	15	65.9	60.8	0.1	1.7	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET030A	3.0	15	66.9	62.4	2.41	1.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET031A	0.0	0	63.2	62.1	0.3	1.1	< 325	709	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET032A	-	Composite	61.5	65.3	0.36	1.3	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET038A	0.1	35	47.9	50.3	0.36	4.4	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET039A	0.5	35	66.2	54.7	0.73	3	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET040A	1	35	73.5	40.3	0.36	4.6	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET041A	1.5	35	76	58.1	0.36	3.9	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800

Sample ID	Depth (m from surface)	Time in storage (days)	Oven Dry matter %	Cellulose %	W/S Carbohydrates%	Total Ash %	Ethanol mg/kg	Acetic acid mg/kg	Propionic acid mg/kg	iso-Butyric acid mg/kg	n-Butyric acid mg/kg	iso-Valeric acid mg/kg	n-Valeric acid mg/kg	iso-Caproic acid mg/kg	n-Caproic acid mg/kg	Lactic acid mg/kg
ET042A	3	35	74.3	55.9	0.36	3.5	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET048A	0.1	64	54.6	55.8	0.37	3	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET049A	0.5	64	63.7	60.3	0.38	3	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET050A	1	64	77.1	64.3	0.37	3.2	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET051A	1.5	64	77.3	56.7	0.37	3.2	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET052A	3	64	75.6	62.3	0.37	2.9	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET053A	0.1	117	52	66	1.19	2.3	<325	<325	<325	<325	<325	<325	<325	<325	<325	2455
ET054A	0.5	117	55.8	63.2	0.39	4.3	<325	<325	<325	<325	<325	<325	<325	<325	<325	1393
ET055A	1	117	65.8	64	0.1	2.5	<325	<325	<325	<325	<325	<325	<325	<325	<325	930
ET056A	1.5	117	72.2	62.1	0.1	1.6	<325	<325	<325	<325	<325	<325	<325	<325	<325	1087
ET057A	3	117	73.1	62.5	0.1	2.2	<325	<325	<325	<325	<325	<325	<325	<325	<325	559
ET060A	0.5	Composite	35.7	67.8	0.4	2.6	<325	<325	<325	<325	<325	<325	<325	<325	<325	<800
ET066A	0.1	216	45	65.2	0.1	2.2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET067A	0.5	216	42.4	76.5	0.1	2.1	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET068A	1	216	71.1	75.4	0.1	1.7	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET069A	1.5	216	74.3	68.5	0.1	2.1	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET070A	3	216	75	71.4	0.1	1.2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET071A	0.1	277	36.2	76.1	0.41	2.2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800

Sample ID	Depth (m from surface)	Time in storage (days)	Oven Dry matter %	Cellu-lose %	W/S Carbo-hydrates%	Total Ash %	Ethan-ol mg/kg	Acetic acid mg/kg	Propi-onic acid mg/kg	iso-Butyric acid mg/kg	n-Butyric acid mg/kg	iso-Valeric acid mg/kg	n-Valeric acid mg/kg	iso-Capr-oic acid mg/kg	n-Capr-oic acid mg/kg	Lactic acid mg/kg
ET072A	0.5	277	60.2	71.1	0.41	1.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET073A	1	277	45.1	68.3	0.41	2.6	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET074A	1.5	277	75.6	68.2	0.4	5.6	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET075A	3	277	62.1	70.1	0.41	2.6	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET081A	0.1	345	38.1	65.6	0.1	1.2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET082A	0.5	345	47.3	53.8	0.1	1.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET083A	1	345	73	56.4	0.1	1.3	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET084A	1.5	345	67.9	54.9	0.1	1.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET085A	3	345	69.5	57.7	0.1	1.1	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET091A	0.1	461	35	68.3	0.34	1.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET092A	0.5	461	75	64.5	0.34	1.7	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET093A	1.0	461	66.4	66.5	0.34	1.6	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET094A	1.5	461	68.8	61.7	0.34	5.2	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET095A	3.0	461	73.1	63.8	0.33	2.3	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET096A	0.1	453	42.2	63.1	0.33	2.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET097A	0.5	453	41.4	57.6	0.33	2.5	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET098A	1.0	453	47.7	57.9	0.33	3.4	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET099A	1.5	453	69.7	59.2	0.33	2.5	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800
ET100A	3.0	453	75.8	61.3	0.33	1.9	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 325	< 800

APPENDIX 5

Table A26. SRC June 2002 bulk density data

Sample No.	Sample depth	Tray No.	Depth	Weight	Bulk density (as received)	Dry bulk density (oven)	Tray weight	Chip Weight	Weight after (chip + tray)	Moisture content (oven)
			(/m)	(/kg)	(/kg/m3)	(/odkg/m3)	(g)	(g)	(g)	(%)
SRC7	3	5	0.53	10.50	177	122	278.11	140.33	374.54	31.28%
SRC8	3	10	0.53	10.90	185	126	278.67	133.68	369.55	32.02%
SRC9	3	8	0.53	10.90	185	120	286.85	159.67	390.12	35.32%
SRC1	1-1.5	29	0.53	15.90	285	129	281.65	229.79	385.61	54.76%
SRC2	1-1.5	25	0.53	13.00	227	122	287.46	180.87	384.62	46.28%
SRC3	1-1.5	32	0.53	13.15	230	129	282.74	159.82	372.5	43.84%
SRC4	0.5-1	4	0.53	25.55	478	138	285.25	359.3	389.31	71.04%
SRC5	0.5-1	30	0.53	25.95	486	128	289.74	373.51	388.02	73.69%
SRC6	0.5-1	31	0.53	24.45	456	122	282.93	354.41	377.94	73.19%
SRC10	0-0.5	6	0.53	19.35	354	117	281.76	297.49	380.38	66.85%
SRC11	0-0.5	7	0.53	19.85	364	129	280.23	272.41	377.01	64.47%
SRC12	0-0.5	9	0.53	18.35	334	120	278.64	308.96	390.1	63.92%

Table A27. Forestry residue June 2002 bulk density data

Sample No.	Sample depth	Tray No.	Depth	Weight	Bulk density (as received)	Dry bulk density (oven)	Tray weight	Chip Weight	Weight after (chip + tray)	Moisture content (oven)
			(/m)	(/kg)	(/kg/m3)	(/odkg/m3)	(g)	(g)	(g)	(%)
FR1	3	14	0.53	16.90	305	221	270.69	205.03	419.45	27.44%
FR2	3	19	0.53	16.20	291	217	269.05	207.29	423.88	25.31%
FR3	3	24	0.53	17.45	316	229	288.33	214.03	443.14	27.67%
FR4	1-1.5	26	0.53	24.00	447	208	286.16	264.9	409.53	53.43%
FR5	1-1.5	27	0.53	21.85	404	219	276.81	271.43	423.76	45.86%
FR6	1-1.5	15	0.53	21.55	398	205	269	243.49	394.64	48.40%
FR7	0.5-1	28	0.53	22.15	410	200	282.85	244.53	402.23	51.18%
FR8	0.5-1	17	0.53	21.70	401	214	268.14	258.46	406.24	46.57%
FR9	0.5-1	13	0.53	20.55	378	185	270.83	236.46	386.53	51.07%
FR10	0-0.5	16	0.53	20.05	368	185	269.32	237.2	388.59	49.72%
FR11	0-0.5	20	0.53	19.35	354	168	267.03	240.82	381.1	52.63%
FR12	0-0.5	18	0.53	19.15	350	174	269.12	221.89	379.27	50.36%

APPENDIX 6

Table A28. Great Heck site details

Distance to Boundary or process (m)	Bearing of sample point from operations (approx)	sample time	Sample Duration (Mins)	Plate Type	Activity	dry temp (^{0}C)	wet temp (^{o}C)	RH %	cloud
10 downwind	180	11:40-11:50	10	acti	pile moved	20.5	14.5	72	6/8
10 downwind	180	11:40-11:50	10	acti	pile moved	20	14.5	73	6/8
10 downwind	180	12:00-12:10	10	oaes	none	20	15	76	6/8
10 downwind	180	12:00-12:10	10	oaes	control	20	15	76	6/8
10 downwind	180	12:10-12:20	10	oaes	control	20	15	76	6/8
10 downwind	180	12:10-12:20	10	oaes	none	20	15	76	7/8
50 upwind	180	12:45-12:55	10	acti	none	21	16.5	78	7/8
50 upwind	180	12:58-13:08	10	oaes	none	21	17	80	1
10 downwind	180	13:20-13:30	10	acti	pile moved	24	15.5	62	4/8
10 downwind	180	13:20-13:30	10	acti	none	24	15.5	62	4/8
10 downwind	180	13:35-13:45	10	oaes	none	20	15	74	2/8
10 downwind	180	13:35-13:45	10	oaes	none	20	15	74	2/8
10 downwind	180	13:50-14:00	10	oaes	none	24	22	90	2/8
10 downwind	180	13:50-14:00	10	oaes	none	24	22	90	2/8
10 downwind	180	14:02-14:12	10	oaes	none	24	22	90	2/8
10 downwind	180	14:02-14:12	10	oaes	none	24	22	90	2/8

APPENDIX 7

Details of NIRS and software operation.

The instrument used in this project was a FOSS NIRSystems 6500 with Winisi software. This comprises of a radiant source usually a tungsten light bulb, a slit to separate the radiant energy into bands, a focusing lens, a wavelength dispersion device (monochromator), another focusing lens, an exit slit and a detector. The sample is presented to the instrument by packing into a cell. These range from ring cups for dried and ground powders to high fat/moisture cells for unground samples. The radiation produced by the instrument is focused onto the sample. If the sample contains small particles the radiation is immediately scattered however some of the radiation will pass through the sample and interact with it, bouncing off and becoming diffuse. This will carry absorption information when it finally reaches the detector. Once the radiation strikes the sample the radiant energy can be absorbed by the colour of the sample or its chemical composition. Colour absorptions cause electronic transitions within an atom. If the sample is an organic substance containing, protein, fibre, oil, or water, the stretching of the CH, OH, and NH bonds will absorb energy in the near infra-red region of the spectrum. This absorption information, along with the scatter, forms the spectrum of the material which is stored as the log of one over reflectance. Colour is defined as the region from 400 to 700nm with a transition region from visible to near infra red between 700 and 1100nm, the near infra red region is defined as 1100 to 2500nm. The NIR region is composed of mainly overtone and combination bands. For instance the primary OH stretch from water is found at 2840nm. Therefore the first overtone is at 1420nm, the second at 940nm and the third at 710nm. The combination band is found at 1950nm. A quantitative approach is achieved by a regression program using the variation in these spectral components to explain the variation in chemistry values obtained from a wet chemistry reference. As the spectrum is unique to the sample, a discriminant analysis program in the software can also use these components to differentiate between samples of a particular product, a qualitative approach.

The instrument can determine if an unknown sample belongs to one of up to 64 groups of known characteristics. This can be samples of the same product from different locations, varieties, ages or a product from differing manufacturing plants, mixtures of different starting materials, detection of a contaminant etc.

The program discriminates by regressing the wavelength information on all of the group values defined as 1 (not a group member eg.species A) or 2 (a group member eg. species B). Each spectrum is then given a predicted value. A predicted value between 1.5 and ~2 is deemed a positive identification and is spectrally similar to the other members in its group file. These values are displayed green on the screen. A predicted value between 0 and 1.5 is a negative identification and is displayed blue. A predicted value of 1.5 can go either way, that is a positive or a negative identification, this is displayed as being an uncertain which is grey on the screen. "Uncertains" around the 1.5 value are caused by the sample having high-predicted values for one or more of the other groups.

If a sample is determined as not belonging to a group while being present in the group file then this is a miss-classification and is displayed red on the screen.
The minimum number of discriminating group files is 2 however the program can accommodate up to 64 group files with a 3000 sample limit in all groups.

When the program has discriminated between groups presented to it a discriminant equation can be generated for routine analysis use, a *.PSD. This file, when used in conjunction with an EQA (NIR analysis equation), PCA (NIR principal component file) and a LIB (NIR library file) file can identify an unknown sample as belonging to a group. It can then go a step further, if needed, by applying the EQA file associated with the product group to predict the chemical composition of the identified sample. An example of applications might be discrimination of forages grown in different areas and even different treatments within these areas, or determining an exact tea blend from many different blends, or determining if an adulterant as accidentally found its way into a product.

Plots of predicted values (wood6.EQA) vs wet chemistry.

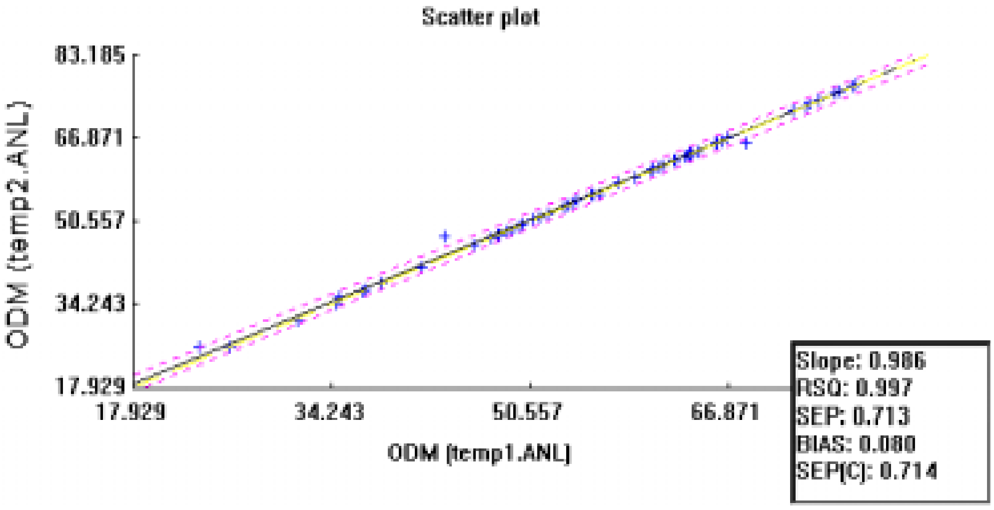

Figure A41 Plot of predicted oven dry matter (x) vs wet chemistry (y)

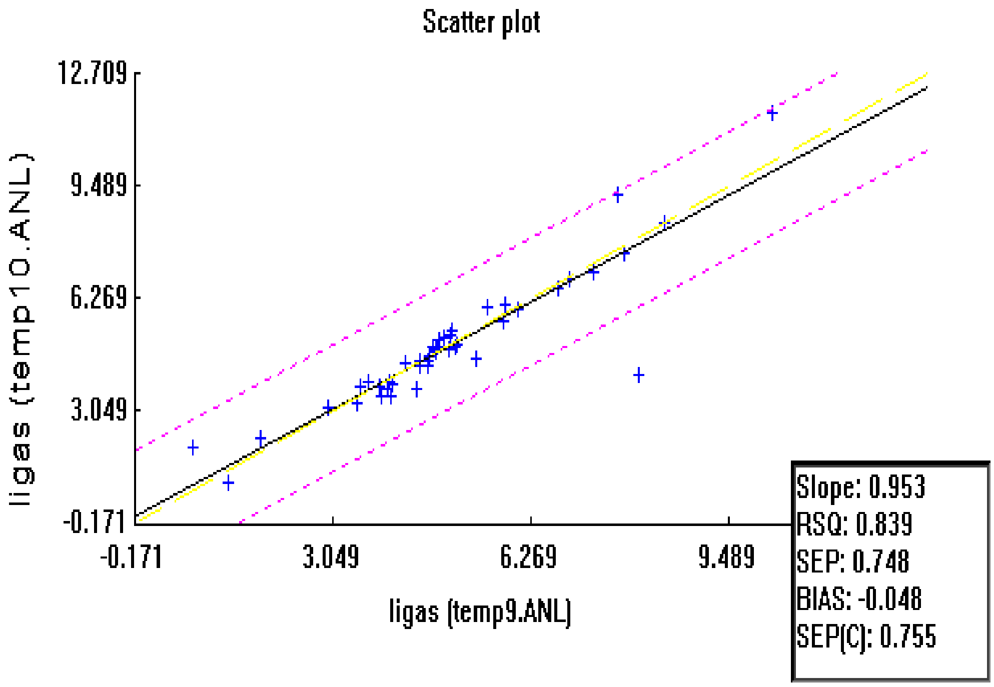

Figure A42 Plot of predicted lignin (x) vs wet chemistry (y). (two outliers removed)

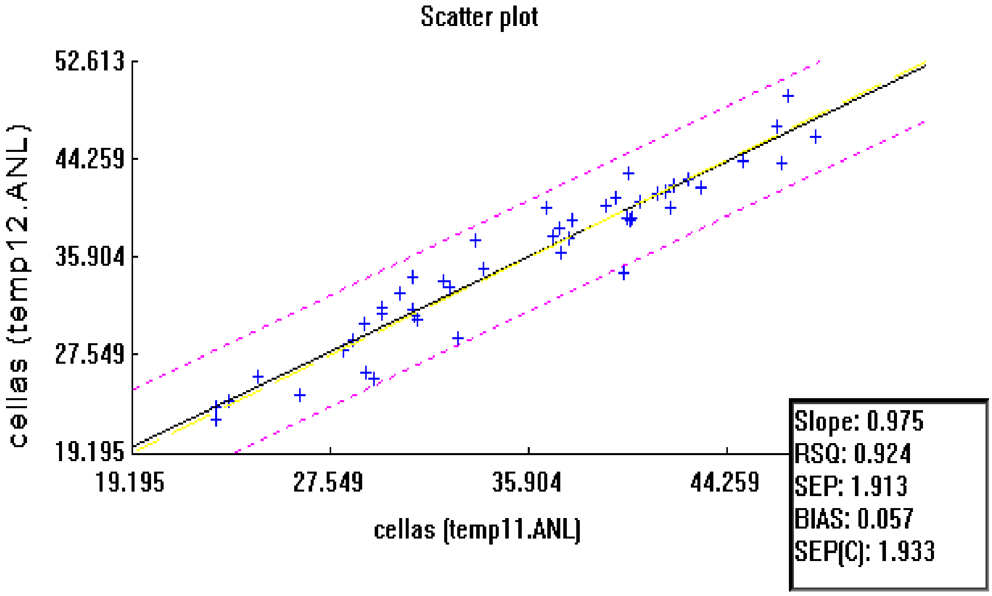

Figure A43: Plot of predicted cellulose (x) vs wet chemistry (y)

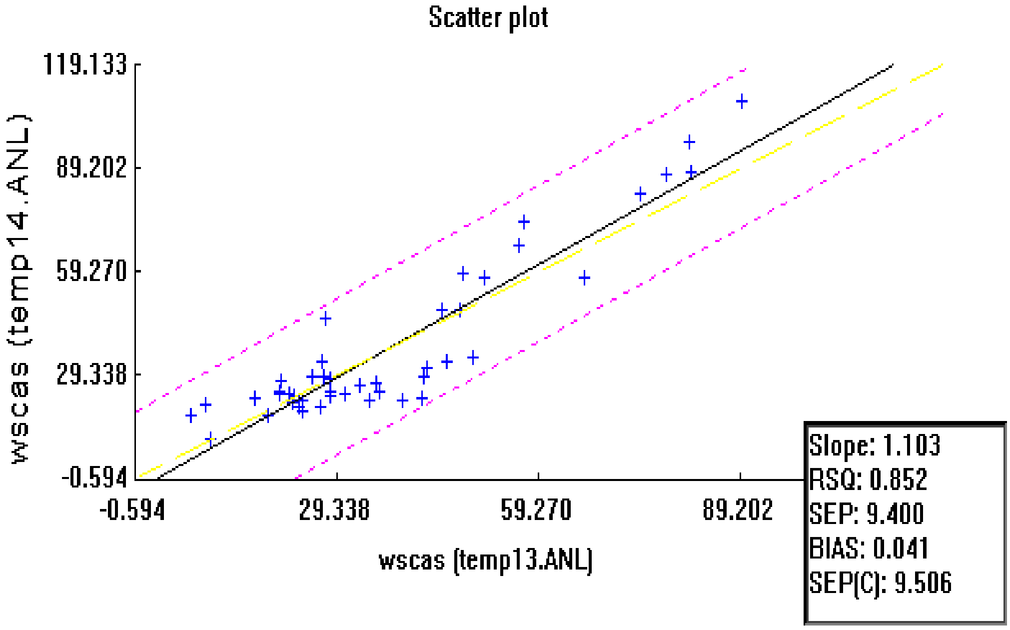

Figure A44: Plot of predicted water soluble carbohydrate (x) vs wet chemistry (y)

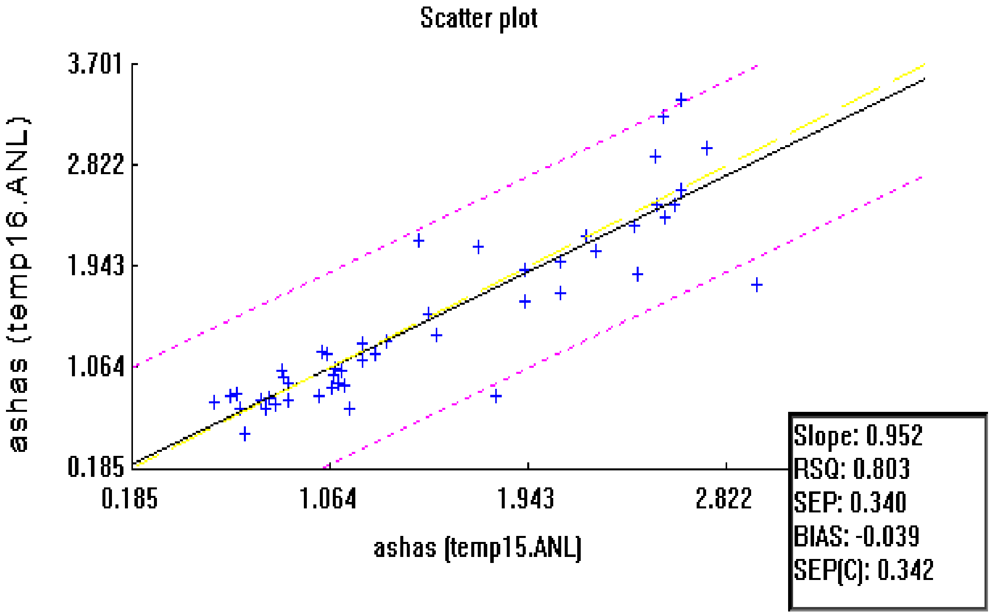

Figure A45: Plot of predicted ash (x) vs wet chemistry (y)

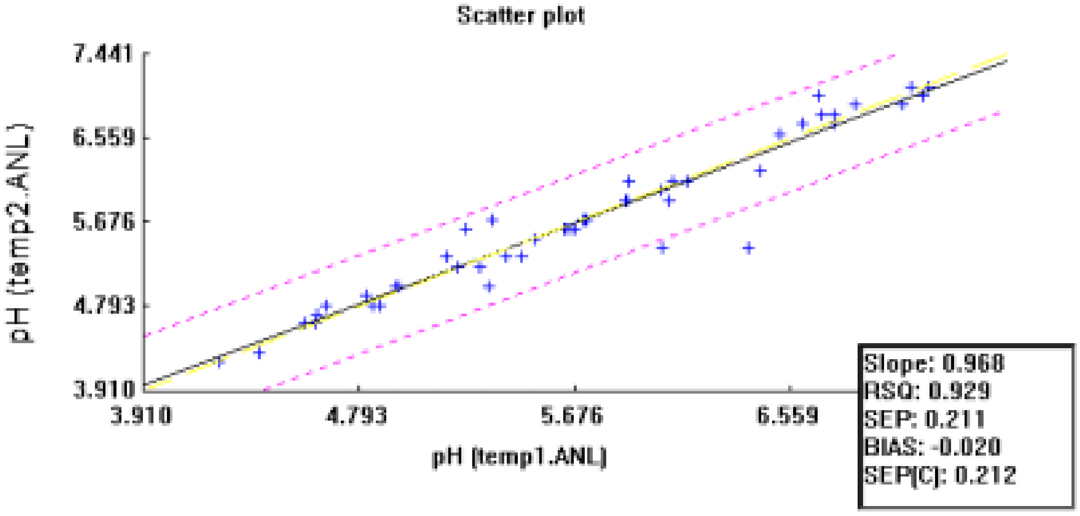

Figure A46: Plot of predicted pH (x) vs wet chemistry (y)