USE OF WOODCHIP FOR AGRICULTURAL LIVESTOCK BEDDING

A thesis submitted to Bangor University

By

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For the degree of

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SUMMARY

Straw price increases due to biofuel demand have created a perceived need within the agricultural industry to investigate and develop alternative bedding materials for housing ruminant livestock. This thesis addresses the suitability of woodchip, as such an alternative, indoor bedding material for livestock, focusing particularly on management of the soiled bedding, its nutrient composition, its use as an agronomic resource and its economic viability within the Welsh farming sector. In all studies, straw was used as the benchmark to which the woodchip treatments were compared. Many studies have investigated the use of woodchip in out-winter pads (OWP), but the material's indoor performance and in particular, its potential for re-use, is not well documented. Two independent housing trials, both including sheep and cattle, were conducted. The first trial (ADAS) assessed the effect of different initial woodchip moisture contents on the performance of the bedding material and its subsequent composting. The second trial (IGER) evaluated the effects of hay and silage diets on woodchip's bedding and composting performance. The ADAS trial showed that woodchip's absorbency capacity and physical shape were critical in determining its bedding and composting success. In comparison to differences determined by bedding materials and livestock characteristics, the IGER trial suggested that dietary inputs had little influence on the woodchip's bedding and composting performance. Overall, the results indicate that composting of spent woodchip bedding was less effective than that of straw bedding, due to the lack of available N which limited microbial activity. The limited breakdown of the woodchips during composting, however, does potentially allow the re-use of the bedding materials for further housing cycles. Barley sown growth trials, amended with composted bedding materials showed that woodchip composts yielded reduced biomass in comparison to conventional NPK based fertilisers and straw bedding compost. When the coarse woody fraction of the compost was removed (>8 mm in diameter), leaving just the fine (< 8mm) nutrient-enriched fraction, plant growth performance was slightly enhanced at application rates equivalent to 100 t ha^{-1}. Estimates of N loss from woodchip treatments were high during housing, but limited during composting due to a generic lack of available nutrients, compared to straw. Using economic modelling, a cost/benefit analysis of woodchip bedding versus straw showed that woodchip is more cost efficient than straw on the condition it is re-used.

In summary, the thesis concludes that woodchip is a potentially viable alternative to straw bedding for Welsh farmers, on condition of specific management practices. Future work is required to identify and mitigate N losses during the woodchip bedding phase.

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For my Father

Kenneth Alexander Paul

16th February 1939 – 29th October 2004

Ecology… ‘‘Well, it’s why elephants are in Africa’’

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LIST OF ABBREVIATIONS

Chapter 1

HCC	Hybu Cig Cymru
WG	Welsh Government

Chapter 3

B:M	Bedding : Manure - The weight ratio of manure to 1 kg of bedding within the compost. Manure refers to all additions to the fresh bedding, predominantly excrement and waste feed, and is determined by; compost weight after housing – total raw bedding added during housing (both sites).
RB	Raw bedding
SB	Soiled bedding
°C	Degrees Celsius

ADAS Raw Bedding

W34	Woodchip with 34% initial moisture content
W53	Woodchip with 53% initial moisture content
W55	Woodchip with 55% initial moisture content
Straw	Straw bedding

IGER Raw Bedding

Wc1	Woodchip delivery 1
Wc2	Woodchip delivery 2
Straw	Straw bedding

ADAS Bedding-Compost Treatments:

S34	Sheep on Woodchip with 34% initial moisture content
S53	Sheep on Woodchip with 53% initial moisture content
S55	Sheep on Woodchip with 55% initial moisture content
SS	Sheep on Straw
C34	Cattle on Woodchip with 34% initial moisture content
C53	Cattle on Woodchip with 53% initial moisture content
C55	Cattle on Woodchip with 55% initial moisture content
CS	Cattle on Straw

IGER Bedding-Compost Treatments:

SSS	Sheep fed Silage on Straw
SSC	Sheep fed Silage on Woodchip
SHS	Sheep fed Hay on Straw
SHC	Sheep fed Hay on Woodchip
CSS	Cattle fed Silage on Straw
CSC	Cattle fed Silage on Woodchip
CHS	Cattle fed Hay on Straw
CHC	Cattle fed Hay on Woodchip

ADAS Treatments: results section

W34	Treatment group of woodchip bedding-composts with 34% initial moisture content
W53	Treatment group of woodchip bedding-composts with 53% initial moisture content
W55	Treatment group of woodchip bedding-composts with 55% initial moisture content
Straw	Treatment group of bedding-composts containing straw
Woodchip	Treatment group of bedding-composts containing woodchip
Sheep	Treatment group of bedding-composts containing sheep inputs
Cattle	Treatment group of bedding-composts containing cattle inputs

IGER Treatments: results section

Straw	Treatment group of bedding-composts containing straw
Woodchip	Treatment group of bedding-composts containing woodchip
Silage	Treatment group of bedding-composts containing silage inputs
Hay	Treatment group of bedding-composts containing hay inputs
Sheep	Treatment group of bedding-composts containing sheep inputs
Cattle	Treatment group of bedding-composts containing cattle inputs
TM	Total Mass (of a compost, or group of composts, or nutrients within a compost, or group of composts) (IGER only)

Nutrient abbreviations

AN	Available nitrogen (this term is used interchangeable with DIN)
AC:N	Available carbon to available nitrogen ratio (# kg TSN to 1 kg of DOC)
AP	Available (soluble) phosphorus
DIN	Dissolved inorganic nitrogen (NO_3^- plus NH_4^+)
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen (TSN minus DIN)
TC	Total carbon
TC:N	Total carbon to total nitrogen ratio (# kg TN to 1 kg of TC)
TN	Total nitrogen
TP	Total phosphorus
TSN	Total soluble nitrogen (DIN plus DON)

General abbreviations

Agric-bedding	Agricultural bedding
D^{-1}	per day
Dy^{-1}	per day
DM	Dry mass (weight)
Manure	Excretal liquids and solids from sheep and cattle
Head	Livestock are counted by the number of 'head'
Hd^{-1}	per head
L-W	Live weights (of livestock)
MC	Moisture content
OWP	Out winter pads – outdoor livestock corrals
Seepage	Effluent drainage from bedding (during housing) or compost (after housing)
Wk.	Week
Wood	Woodchip
w/w	Wet weight (mass)
WW	Wet weight (mass)
Yr.	Year

Chapter 4

FAd	Forced air dried
NAd	Naturally air dried
WAC	Woodchip absorbency capacity
WDPT	Water drip penetration test

1.1 General introduction and need for research

Increasingly variable weather conditions and bulk demand from the expanding biofuels industry are forecast to increase significantly the cost of straw available for animal bedding throughout the UK. This will particularly affect Welsh farmers, especially if the rising cost of straw is coupled with rising oil prices. This is because the topography, climate and primary soil type in Wales do not allow sufficient cereal production to satisfy the nation's straw bedding requirements. As such, on top of the basic cost of straw, most Welsh farmers have to pay a substantial haulage cost, exposing them to the risk of increases in the price of fuel.

These two factors create the need for a sustainable substitute to bridge the gap when straw prices become too high. In light of these combined and mounting pressures, the Welsh Government (WG) commissioned this research project to investigate the feasibility of using woodchip as an alternative to straw bedding, with emphasis on the material's long-term environmental and economic sustainability. There are a variety of suitable, locally sourced materials available to farmers in different regions of Wales. However, straw is currently the most popular bedding type, and is estimated to cost the nation's farming industry £12.5m per annum. Conversely, wood is a comparatively abundant resource in Wales, and interest in the use of locally sourced wood fuel is gaining momentum. This would allow an emerging woodchip transport industry to take advantage of infrastructural developments initiated by growth in domestic woodchip fuel demand, to supply agricultural premises with woodchip for animal bedding.

The Woodchip for Livestock Bedding Project ran from December 2005 until May 2008 to evaluate the potential of woodchip as an alternative indoor bedding material to straw, for use under sheep and cattle during the winter housing period. The project was funded by the WG via Farming Connect Objective 1 monies, the Forestry Commission Wales and the Environment Agency Wales. The project was executed under the co-ordination of Hybu Cig Cymru (HCC) by a multi-party collaboration, principally including Bangor University, IGER Aberystwyth, ADAS Pwllpeiran and Glynllifon College, with a participatory contribution from Aberystwyth University.

The candidate enrolled as a PhD student at Bangor University, funded by the WG, in March 2006, which coincided with the project's composting phase. As the Bangor University representative, the candidate's primary role was to sample, analyse and report on the composting performance of bedding-compost treatments from housing trials conducted at ADAS and IGER. After the composting phase, the candidate determined and reported the product's agronomic value through a series of comparative growth trials; reviewed and summarised legislation surrounding the finished product's sale, distribution and agronomic application; and developed an economic model to fully appraise the material's economic viability in comparison to straw bedding. In addition, HCC conducted 10 on-farm woodchip housing trials and open days, at private farms throughout Wales, in order to demonstrate the material's efficacy directly to the general public. It was the candidate's role to attend each open day and advise farmers through PowerPoint presentations and question and answer sessions on all aspects of using woodchip as winter bedding.

1.2 Plan of thesis

The experimental chapters of this thesis comprise three empirical areas of investigation from the parent project: composting processes, agronomic evaluation of the compost and an economic appraisal of woodchip within an agricultural context. A general theme of nitrogen cycling and budgeting links all three experimental chapters, with empirical data used where possible, the remaining data being estimated from external sources.

Chapter 2 provides a contextual framework through a review of the issues surrounding the project, such as current UK agricultural policy and related markets and industry structure, before moving on to critically evaluate a range of novel bedding materials and housing systems and the resulting livestock performance. The chapter concludes with a general overview of composting dynamics and fertility value.

Chapter 3 describes the processes of composting woodchip bedding with controlled initial feedstock variables, initial moisture content and livestock dietary inputs. Results are presented in full to provide a clear appraisal of the composting process, although the discussion focuses on the influence the different initial moisture contents in the woodchips (at ADAS) and dry vs. wet feeds (at IGER) had on decomposition. This is followed by more general discussion of nutrient dynamics, especially nitrogen in the contrasting composts. The chapter concludes with a comparative assessment of the beddings' nitrogen budgets.

Chapter 4 examines the agronomic value of a selected range of composted amendments, assessed through a series of grass and barley growth trials using a range of application rates.

Chapter 5 appraises the economic viability of woodchip as an indoor winter bedding in comparison to straw, based on DEFRA prescribed housing densities for sheep and cattle and the Government project's recommendation that composted woodchip be re-used as bedding over a number of winter housing periods, on condition that relevant UK PAS100 regulations are satisfied each summer.

Chapter 6 draws conclusions from the three previous experimental chapters and identifies areas of further work. Appendices consist of additional work carried out to support the results presented in the main experimental chapters.

1.3 Aims and objectives

The aims, objectives, protocols and outcomes of this research were agreed with the funding body prior to the candidate's enrolment at Bangor University. The project structure was agreed as follows:

- **Housing trials:** to be carried out under a variety of different conditions. The objective was to assess the usability and performance of woodchip independently and in comparison to straw as winter bedding. Conducted by ADAS, IGER and Glynllifon College in association with HCC, prior to Bangor University's involvement.

- **Compost quality:** the soiled bedding's performance and nutrient status were to be monitored during and after composting. The objective was to establish the composts' value as a fertiliser and develop a timescale for the woodchip's use as bedding before being applied to the field (Chapter 3).

- **Compost markets:** potential markets were to be investigated for composted woodchips in agronomic, horticultural and industrial settings, with the objective of establishing end-use options for woodchip/manure compost and validating markets (Appendix III).

- **Compost agronomy:** the agronomic benefit of composted woodchips was to be investigated within a range of agricultural contexts. The objective was to establish the optimal use of woodchips with the aim of providing practical guidance to farmers and developing market confidence in composted woodchip products (Chapter 4).

- **Economic appraisal:** current costs of sourcing, using and composting woodchip bedding were to be assessed in comparison to other conventional agronomic options (e.g. fertiliser, straw etc.). The objective was to establish the cost-effectiveness of using composted woodchips in agriculture (Chapter 5).

2.1 Introduction

The majority of land in Wales is either occupied by farm holdings or is common land (which equates to 1.7 million hectares (Mha) of a total national land area of 2.1 Mha). Most of the nation's agricultural land is used to graze livestock (1.45 Mha), as the soil quality, altitude and climate restrict arable crops to coastal areas and sheltered valleys (Welsh Government, 2012). There are 8.62 million sheep, mostly in upland areas, accounting for around 27 % of the UK total, and 1.1 million cattle, 11 % of the UK total (Welsh Government, 2012). The majority of agricultural activity in Wales takes place on small to medium sized farms. The average holding size in Wales is 37 ha; in England 85 ha; in Scotland 107 ha and in Northern Ireland 41 ha (DEFRA(a), 2011).

Table 2.1: Agricultural land use in Wales

Agricultural area ('000 ha)	2001	2009	2010	2011
Total area	1,623	1,670	1,710	1,713
Permanent grass	974	1,027	1,021	1,045
Rough grazing[(a)]	408	394	410	404
Arable land	184	172	190	206
Woodland and other land	56	78	90	57

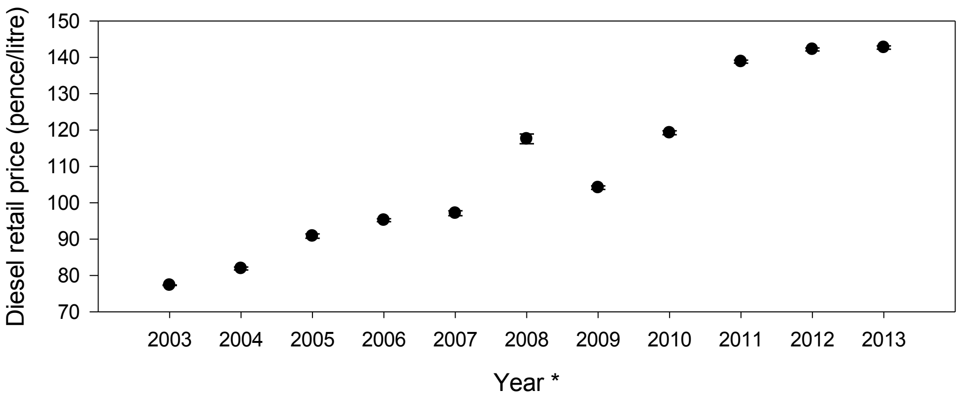
(a) Includes common grazing
Source: Farming Facts and Figures: Wales 2012; June Agricultural Survey

2.1.1 The livestock bedding market and related issues

2.1.1.1 Straw

Among the escalating financial challenges expected to face British farming in the near future is the increasing demand for straw from the rapidly expanding biomass industry. The UK Government's Biomass Strategy (BEC, 2007) adopted the recommendation made by the Biomass Task Force (DEFRA, 2005) that one third (3 – 3.3 Mt) of straw produced in the UK each year could be made available to the biomass industry in the long term, without disruption to livestock use or buying costs. Between 2009 and 2011, the area of wheat farmed in the UK increased from 1.78 Mha to 1.97 Mha. However, the area of total (winter and spring) barley decreased from 1.14 to 0.97 Mha (DEFRA(a), 2011). The UK Government's Biomass Energy Centre estimates wheat and barley straw yield to be 3.5 t /ha and 2.75 t /ha respectively (BEC(a), 2011); although yield is dependent on a wide range of factors, not least cultivar choice and climatic conditions. For example, actual wheat straw yield in 2007 was 3.46 t /ha and barley straw 2.68 t /ha. Variation is due to the complex pressures growers face when choosing cultivar varieties and sowing times: considerations include soil type, moisture and nutrient status, fertiliser costs and increasingly variable seasonal conditions, as well as the need to forecast market demand. Dry winters result in higher spring soil N contents than wet winters. If this is not accounted for in spring fertiliser dressings it can lead to rapid early growth and weak stems, increasing the risk of root lodging. To avoid this, growers often use 'shorteners' – growth regulating hormones that produce shorter, broader straws. However, stems that are short and, particularly, brittle cannot be processed into round bales as efficiently as long stems; with escalating fertiliser costs, many farmers chose to plough the straw back into the soil (Doyle; The Irish Farmers Journal, 2012).

In 2011, the area of wheat cropped in the UK was 1.97 Mha and 0.97 Mha of barley, which, by the Biomass Energy Centre's yield estimates, produced 6.89 Mt and 2.67 Mt of straw respectively. In addition, 109,000 ha of oats potentially generated 430,000 tonnes of straw (although oat straw is most commonly used as equine bedding); 0.7 Mha of oilseed rape offered a potential total yield of 1 Mt of rape straw (DEFRA(b), 2011). However, this is generally too friable for use as livestock bedding. In summary, UK straw production in 2011 was approximately 10 Mt, excluding oilseed residues (BEC(a), 2011). In 2004, only 200,000 tonnes of straw were burnt for energy, but from 2003 to 2010, the average annual £ /t for Hesston (large sized bales) wheat straw increased 185 %, from £16 to £45; even allowing for climate-driven price rises, that is a mean increase of 23.1 % pa. The combined average price of (Hesston baled) barley and wheat straw rose by 22.5 % pa over the same period (DEFRA(b), 2011). It is acknowledged that 2003 straw prices were unusually low; however, these are ex-farm prices, so exclude the cost of haulage. The retail diesel price litre^{-1} increased 42 % between January 2003 and January 2008 (and 74 % between January 2003 and the high of July 2008). At the time of writing, the 2013 average retail price of diesel is 142.68 pence litre^{-1} and the average national wholesale price per tonne of Hesston baled wheat straw is £59. This highlights the escalating financial pressure the Welsh agricultural community has been under since this project was completed.



Source: DECC 2013 – Office of National Statistics – Weekly Fuel Prices, June 2003 - April 2013.

Figure 2.1: *Average annual retail ultra-low sulphur diesel (ULSD) fuel prices 2003-13 ± 1 se. Year* historical weekly price records were available from Jun 2003 to April 2013 (present).*

It is unknown if, or to what extent, the British government's estimated annual UK straw production of 9 to 10 Mt takes into account the increasingly variable climate, or whether the assignment of one third of the UK's annual straw harvest by the Biomass Task Force (DEFRA, 2005) is a cautious estimate that will safeguard a rolling reserve for agriculture if a harvest fails. Furthermore, if these divisions of the UK straw stock were to become entrenched, it is likely the biomass industry would seek to secure 5 year, fixed price/volume contracts with growers, similar to those used by major supermarkets. In the past these have provided producers with the opportunity of a guaranteed income that allows them the financial flexibility to plan ahead. However, in poor harvest years, fixed volume contracts would result in the straw bedding market absorbing all the shortfall between the total yield and the biomass industry's contracted claim, potentially forcing prices to uneconomic levels and destabilizing the market. In addition, novel factors influencing demand in the biomass market that previously had little or no effect on availability of straw for livestock bedding - such as sharp increases in fossil fuel prices or legislative changes to aviation fuel duty - will generate significant and unexpected competition. This is because at least some, financially flexible, farmers will switch production to grow these cash crops. Furthermore, it is difficult to conceive how the UK Government could legislate against bioenergy producers buying more than their recommended quota within a free market, if demand exists.

Agriculture across Europe is facing narrower profit margins under the current global economic downturn. However, there is a particularly acute and protracted paradox in Wales: Welsh lamb is renowned the world over, but Welsh hill farming is perhaps the poorest sector within the UK's agriculture portfolio. Farmer's profit margins are squeezed between a small number of large-scale animal feed and agrochemical suppliers and the well-documented buying power of the major supermarkets, leaving little flexibility for individual farmers to increase their earnings. Indeed, profit-driven cost cutting in the animal feed manufacturing industry was thought to have been the cause of the BSE epidemic during the 1980s. Dr. Wilesmith's initial conclusion to the BSE Inquiry, published in Oct 2000 stated:

> …cattle were exposed to the scrapie agent via sheep offal present in cattle feedstuffs and […] cattle became infected following changes in rendering methods which resulted in either a cessation or a reduction of inactivation of the scrapie agent…
> (BSE Inquiry, 2000).

This causal prognosis has since been disputed - but the cost cutting actions of the feed manufacturers have not.

As previously mentioned, market instability is also exacerbated by the responsiveness of a few large-scale, affluent operators to changes in government policy and economic trends, generating a collective shock to national markets when little or no supply-side slack exists. Between 2007 and 2008, the total land area in the UK planted with cereal crops increased by 13 %, whereas the total number of sheep and cattle decreased by 2.4 % and 1.9 % respectively. These decreases were amplified in Wales: there was a 5 % reduction in sheep numbers and a 2 % reduction in cattle numbers during 2007-08 (DEFRA, 2008). While this ephemeral flux eases the strain on straw bedding prices within the annual cycle, it highlights an erratic inter-relationship of supply and demand between cereal and livestock markets.

The 2005 EU CAP reforms push farmers to be innovative and diversify, but rapid diversification to take advantage of market trends requires considerable existing capital. Therefore, it is only affordable to a small percentage of large-scale individual or corporate operators, which leaves the majority of farmers facing financial paralysis, many of them having already gone bankrupt. The total number of 'dormant' holdings in Wales increased by 66 % between 2003 and 2011, while the number of 'livestock-only' registered holdings fell by 17 % over the same period (Welsh Government 2007 and 2012).

Table 2.2: Number of holdings in different farming sectors

Type of farming:	2003	2009	2010	2011	± % change 2003 - 2011
Cereals	269	394	388	415	54.3
General cropping	98	148	119	123	25.5
Horticulture	423	332	337	457	8.04
Dairy	3,015	2,094	1,984	1,908	-36.7
Cattle + sheep (LFA)	11,899	11,425	10,897	10,941	-8.05
Cattle + sheep (non LFA)	3,028	2,169	2,032	2,046	-32.4
Mixed (crop + livestock)	608	796	750	775	27.5
Minor holdings	2,564	3,771	4,263	4,126	60.9
Dormant holdings	10,686	15,140	16,731	17,765	66.2
All types	35,499	39,024	40,168	40,900	15.2

Source: Farming Facts and Figures: Wales, 2007 and 2012

2.1.1.2 Biomass

Biomass is the generic term for material derived from growing plants or from animal manure. Bioenergy refers to the technical systems through which biomass is converted and used as an energy source. A wide variety of conversion routes have been developed that produce a variety of fuels in a solid, liquid or gaseous form. These fuels address all types of energy markets: heat, electricity and transportation. In the EU-27 (the European Union, including accession countries), bioenergy constitutes only 3.7 % of the total primary energy supply, but 20 % of Finland's gross inland consumption and 16 % of Sweden's (EUBIA, 2007).

In 1995, Nielsen concluded a 3-year study on behalf of the International Energy Agency (IEA), stating that straw was problematic as a fuel for heat and power production, because it did not offer reasonable power efficiencies, or stable operational and environmental conditions at acceptable economies of scale. However, the economic problems were in relation to the procurement and delivery costs of predominantly Hesston baled straw in Austria, Denmark, Holland, and Sweden - but not the UK. Today, there are 5 straw-fired biomass plants under various stages of development (BEC(b), 2011) at Tansterne, Hull (operated by GB BIO Ltd) with capacity to burn 75,000 tonnes of straw per annum; Wetwang in Yorkshire (East Yorkshire Power Ltd) which will have an output of 15 megawatts (MW) generated from burning both wood and straw (1MW requires approx.10,000 tonnes of wood or 6,000 tonnes of straw (BEC(b), 2011)); and three others at Brigg, North Lincs; Mendlesham, Suffolk and Sleaford, Lincs, all operated by Eco2 Ltd and each with the capacity to burn 240,000 t straw pa (Eco2, 2012). The straw is either used directly, in the form of bales, or torrefied into pellets. Torrefaction (drying or roasting) of straw with pelletisation increases the energy density of the resource, further reducing transport costs per tonne. This processing step also makes the pellets hydrophobic and therefore easier to store. Torrefied pellets can be directly co-fired with coal or natural gas at very high rates, and thus can make use of existing processing infrastructure. This enables a low cost, emission-saving transition from fossil fuel use in power stations. However, pellets are limited to a co-firing rate of 15 % in modern Integrated Gasification Combined Cycle (IGCC) power plants.

2.1.1.3 Biofuels

There is a wide range of existing biofuels, and efforts are on-going to develop still more. Each fuel type is defined by its feedstock and the processing method thereof. They include vegetable oil, biodiesel, bioalcohols, bioethers, biogas, syngas and solid biofuels. Of these, biodiesel (oil-based) and bio-alcohols (fermented sugars) are the principal fuel types (Pistonesi et al., 2008).

Bio-sugars are fermented to produce bioethanol, in a similar process to that used in beer and wine making (see Figure 2.2). All vegetative materials (grain, stems and leaves) are composed of sugars in various amounts, so in principle almost any plant can serve as a feedstock. In practice, the choice of raw material depends on the local climate, landscape and soil type, as well as the sugar content and processing ease of the various plants available. First generation (1G) biofuels use the most sugar-rich 'food' part of the crop. The most common feedstocks are sugar cane, sugar beet and cereal seeds and grains.

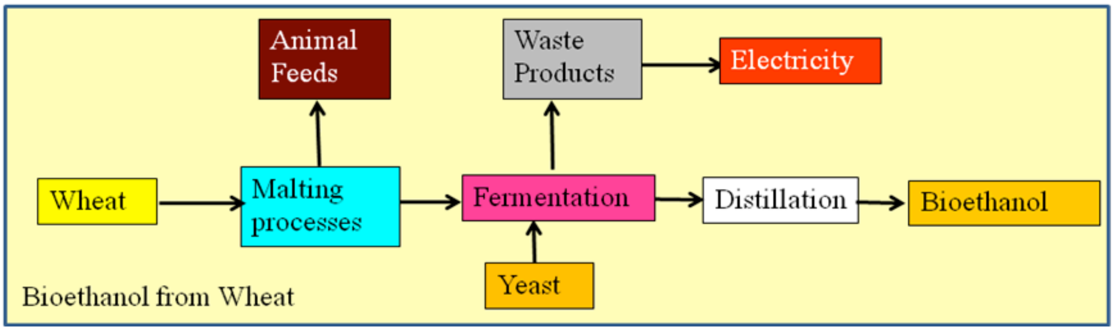


Figure 2.2: *Bioethanol production from wheat using malting and fermentation. (Tovey, CRed UEA, 2008)*

In 2008, this co-demand caused sharp increases in global food prices, and, in poorer countries such as Haiti, led to shortages and social unrest. Furthermore, food crops require considerable amounts of agro-chemicals, particularly fertilisers - which defeats the primary purpose of bioenergy: reducing greenhouse gas (GHG) emissions compared to fossil fuels.

In an effort to mitigate this carbon cost, second generation (2G) biofuel technologies are being developed to process the residual, non-food parts of crops such as straw and sugar cane, as well as non-food crops such as miscanthus, jatropha and eucalyptus, forest residues, waste woods, and municipal solid wastes. The biofuels industry promotes 2G fuels as low cost, having a higher net energy balance and the potential to save up to 90 % in GHG emissions - based on the premise that the 2G feedstock was previously a waste by-product and, therefore, that the agrochemical carbon input is attributable to the production of grain for food. Figure 2.3 illustrates the process by which 2G bioethanol is produced from waste by-products, namely straw and wood. However, these non-food materials contain less sugar than grain does. It also tends to be locked in relatively inaccessible molecular structures and is therefore more expensive to process (ePURE, 2011). 2G biofuels are likely to broaden the scope for UK feedstock supply and may result in a calorific pricing structure for all organic 'waste' products, particularly straw - which has a relatively high biomass potential - resulting in a dysfunctional pricing mechanism for the livestock bedding market. In addition, high biomass crops such as miscanthus, short-rotation coppice (SRC) and maize are expected to broaden the geographical area suited to feedstock production and could thus, depending on prevailing market conditions, reduce the area used for straw-producing cereal crops.

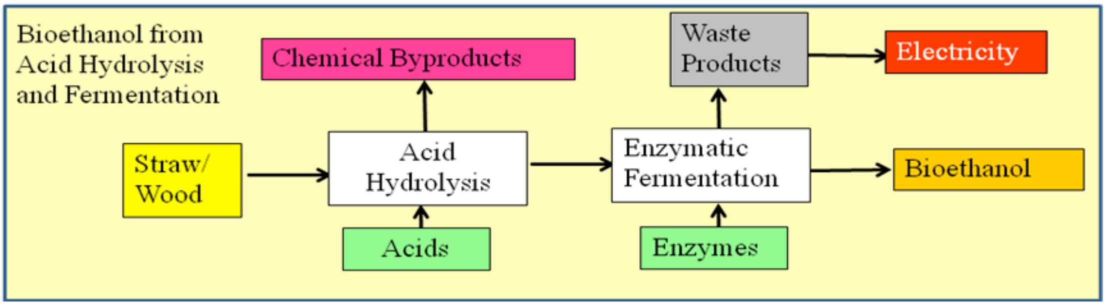


Figure 2.3: *Bioethanol production from wood or straw by acid hydrolysis and fermentation. (Tovey, CRed UEA, 2008)*

Worldwide, most bioethanol is derived from sugar cane. In 2006, Brazil produced 18.3 billion litres (Bl) from sugar cane. The USA produced 15.7 Bl from molasses and corn, while Europe generated 1.6 Bl from wheat, barley, rye and sugar beet (Worldwatch Institute, 2007). Grain crops such as wheat, with a high starch content that has to be converted to sugars first, yield on average 0.875 tonnes of oil equivalent (toe) /ha, compared to sugar beet (2.65toe /ha) in the EU (EUBIA, 2007).

Table 2.3: Bioethanol produced by some EU states 2004 – 09 (million litres)

Country	2004	2005	2006	2007	2008	2009
France	101	144	293	539	1000	1250
Germany	25	165	431	394	568	750
Spain	254	303	396	348	317	465
Lithuania	0	8	18	20	20	30
UK	0	0	0	20	75	70
EU Total	**528**	**913**	**1593**	**1731**	**2816**	**3702**

Source: ePURE

Europe has a bioethanol production capacity (PC) of 7,252 Ml pa, produced mostly from sugar juice, raw alcohol and wheat (see Table 2.3). However, there is a further 1,751 Ml pa of capacity under construction, which will be mainly derived from wheat (ePURE, 2011).

At the time of writing, only British Sugar in Norfolk has operating bioethanol production facilities, with a capacity of 70 Ml from sugar beet. However, there are three major construction projects underway: Ensus Plc. on Teesside, with a PC of 400 Ml pa (completed in 2010); Vivergo Fuels Ltd in Hull (PC 420 Ml pa) and Vireol Ltd near Grimsby (PC 200 Ml pa). Both will process wheat, giving the UK a potential capacity of 1 Bl pa (EUBIA, 2007; ePURE 2011). This would represent approximately 2 % of the total road transport fuel consumption (49,035 Ml) used in the UK during 2006 (Tovey, CRed 2008). Interestingly, if every hectare of wheat (bioethanol) and oilseed rape (biodiesel) grown in the UK during 2006 (including 466,000 ha of set-aside, split 50:50), had been given over to the production of 1G biofuel, it would have yielded 6,517 Ml or 13.3 % of the total road fuel used that year.

In 2005, the UK government announced the Renewable Transport Fuels Obligation (RTFO) which requires that, by 2010, at least 5 % (by volume) of all transport fuel is biofuel, with a provision for further increases to follow. Using figures published by NNFCC, it is estimated (assuming a 50:50 split between biodiesel and bioethanol), that approximately 0.87 Mha of oilseed rape and 0.5 Mha of wheat will need to be grown in the UK just to meet this transport target.

The UK boasts the highest wheat yields in the world, averaging 7.88 t/ha between 2005 and 2009 (DEFRA, 2009), and the EUBIA estimates UK bioethanol yields from wheat to be 2,686 l/ha (3:1 (t) output ratio). Therefore at maximum capacity, the two refineries at Teesside and Hull will process 305,287 ha – 17 % of the UK's 2007 field-grown wheat harvest. However, in June 2007, there was 438,000 ha of set-aside land (which can be used for energy cropping, but does not qualify for the Energy Aid Payment of €45 /ha (NNFCC) that in-field produce attracts). By 2008 arable set-aside had fallen by 67 % to just under 194,000 ha (DEFRA(b), 2010). This was in response to the EU's 0 % set-aside requirement, designed to increase grain production and control rising food prices (Clarke, 2007).

2G straw can only produce around 290 litres of bioethanol per tonne of dry material, compared to 420 l/t of 1G wheat grain, which is 31 % less w/w (density of bioethanol: 0.789 kg /litre). So, hypothetically, if the refineries in Teesside and Hull were converted to process 2G straw, they would need 2.83 Mt of torrefied straw, or - more realistically - 3.1 Mt at 10 % moisture content to meet their combined capacity. In a poor harvest that would represent all, if not more than, the biomass industry's Government-recommended straw quota.

2.1.1.4 Wood

In 2005, only 12 % of the total land surface of Wales was under forestry and woodland. 8 % was urban and miscellaneous land, and the remaining 80 % was under agricultural production (Welsh Government, 2006). However, the nation's forested land area was representative of the rest of the UK. It is low in comparison with other areas of the world. The EU's average is 37 %, while Europe's and Russia's combined is 44 %; North and Central America have 33 %; Asia 19 % and Africa 21 % (Forestry Commission, 2008). It is perhaps not surprising that the UK had a 3.7 Mt wood trade deficit in 2007. Nevertheless, within this macrotrading portfolio, the woodfuels market, significant for establishing an industrial and commercial infrastructure within which woodchip for livestock bedding can operate, roughly doubled in Wales between 2004 and 2007. Softwood deliveries increased from 100,000 to 200,000 t between 2006 and 2007 and hardwood deliveries increased from 150,000 to 300,000 t between 2004 and 2007 (Forestry Commission, 2008). Woodchip has historically been a non-commercial by-product of forestry/woodland management, municipal transport departments and private commercial operators. However recent spikes in conventional energy prices combined with growing public concern over CO_2 emissions have generated strong demand for pre-chipped woodfuel. As a result, for 10-tonne minimum deliveries, suppliers in 2010 were charging on average £80 /t (range £60 - £90) at 30 % moisture or £107 /odt (oven dried tonne) (DECC, 2010). However the DECC forecast international wood fuel supplies to increase up to 2030, and the average cost in real terms to fall to £55 /odt by 2015 to £40 /odt by 2020 and £24 /odt by 2030 at current exchange rates.

2.1.2 Sustainability

During the Second World War, the German strategy of using U-boats to besiege Britain led to serious concerns for food security. At that time, agricultural policy was not high on the agenda, so food production was ‘by any means necessary’. In 1947, the government introduced the Agriculture Act, which, in essence, served as a precursor to the European Common Agricultural Policy (CAP), established following the signing of the Treaty of Rome in 1957 and the creation of the EEC on 1st January 1958. Both policies’ key objectives were to increase agricultural productivity and self-sufficiency, stabilise markets and ensure low prices for consumers, as illustrated in Figure 2.4. To facilitate these objectives, the EU supported production and capital costs though blue box measures (see Figure 2.4) such as land drainage and headage payments, while simultaneously using interventionist buying tactics and distorted trade tariffs to create a false floor market – amber box measures.

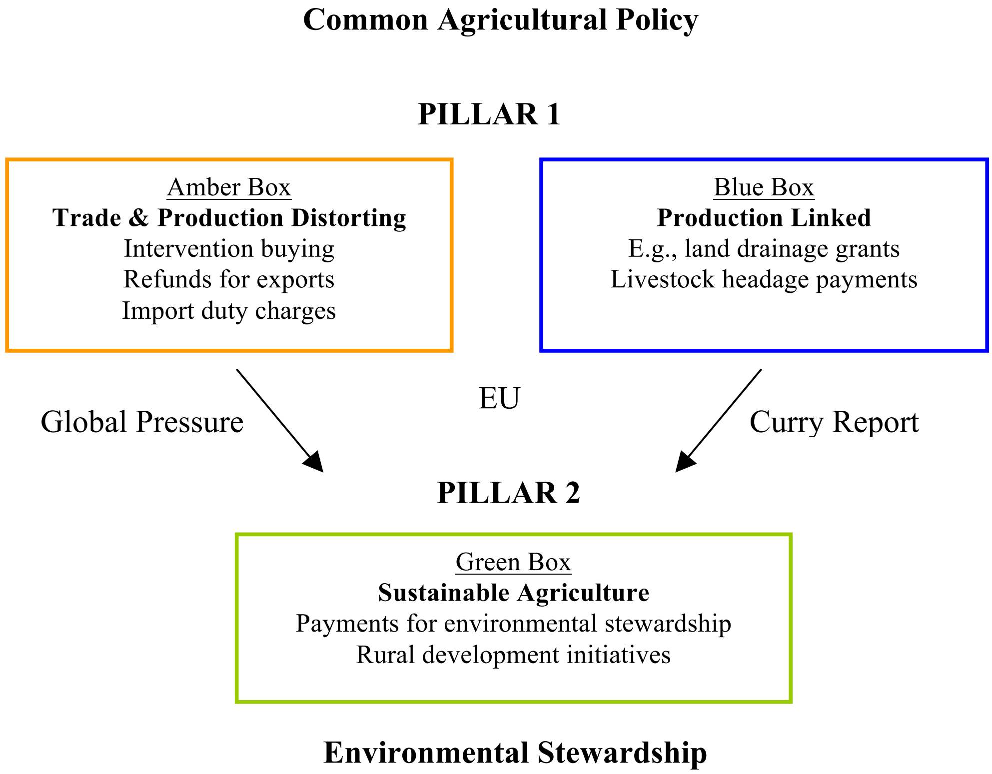


Figure 2.4: *Transition from pillar 1 (amber & blue box) to pillar 2 (green box), in 2005.*

In the late 1940s and 50s, European commitment to intensive agricultural production was boosted by the global development and availability of agro-chemicals (Murphy, 2005; Ogaji, 2005). Miller (2002) states that developed world agriculture is responsible for 75 % of global pesticide use, which Edwards (1994) estimated to be nearly 2.5 Mt /pa., made up of 45 % herbicides, 30 % insecticides, 19 % fungicides and 6 % other pesticides. This total mass represents a 32-fold global increase since 1950, with a total value of nearly $30 billion.

In 2002, global fertiliser use was 141.5 Mt. The UK was the thirteenth highest-consuming nation, applying 1.8 Mt - equivalent to 30.4 kg per person (WDId, 2002). The average wheat yield in the UK from 1885 to 1959 was 2.5 t /ha, but jumped to an average of 6 t /ha from 1960 to 2008 (DEFRA(a) 2010). However, in addition to the environmental hazards caused by nutrient run-off, such as the eutrophication of surrounding watercourses, Ames (1979) suggested that excess use of agro-chemicals may cause increased incidences of cancer in humans and other potential exposure-related hazards.

Throughout the European CAP zone, subsidised production and the extensive use of agrochemicals over the last fifty years has resulted in broad and devastating shifts in land use and soil nutrient balances. Non-productive areas such as woodlands and heaths have been cleared for commercial use, hedgerows removed to maximise existing field areas and traditional farming practices such as break-cropping, under-sown-leys and fallow land have been increasingly abandoned. In combination, these changes have contributed to a catastrophic decline in farmland birds (Fuller et al., 1995; Chamberlain et al., 2000; Donald et al., 2002; Benton et al., 2003). The use of high doses of pesticides on arable land not only destroys both herbivorous pests and beneficial predatory invertebrates alike - which Pimentel et al. (1993) estimates costs the USA alone $540 million /yr. - but also eradicates the primary trophic level of many complex food webs, unravelling a network of biotic inter-dependencies and replacing it with a costly, vulnerable and environmentally unsustainable platform of chemo-crop dependency. However, with the emergence of energy-cropping and the hard lessons learnt from a produce-centric CAP, Bellamy et al. (2009) has shown that, compared to wheat, miscanthus energy crops are more beneficial to bird populations before the canopy develops, inhibiting wild ground flora. They argue that profit-restrained, regulated management techniques must be established now, before industry practices become entrenched, if any significant benefit to biodiversity is to be realised. This issue was first publicised by the environmental lobby in the early 1980s, leading to the creation of the Wildlife and Countryside Act, 1981. Although this policy was not well received by the farming community, it marked the start of a U-turn in agricultural policy by re-introducing the notion of environmental sensitivity. Agro-environmental schemes such as the demarcation of Environmentally Sensitive Areas (ESA) followed in 1987 and the Countryside Stewardship Scheme (CSS) in 1991, but these were voluntary, incentive-based and farm-specific, so were not integrated on a landscape, ecosystem or even habitat level.

In 2002, the Curry Commission recommended public policy's main objective should be:

> …to reconnect our farming and food industry: to reconnect our farming with its market and the rest of the food chain: to reconnect the food chain with the countryside; and to reconnect consumers with what they eat and how it is produced. (Curry et al., 2002)

The commission urged policy makers to evaluate the true cost of intensive production generated by Pillar 1 measures and to engage with an inclusive philosophy, combining wildlife habitat regeneration and local cultural heritage with quality and diversity of primary produce, which in turn would benefit the direct consumer and the broader community. The Curry Commission was used as the basis of the UK Government's Environmental Stewardship Scheme in 2005. At a European level, pressure to reform the production-based CAP was reportedly brought about by the convergence of a number of widely varying factors:

- The USA, via the World Trade Organisation, lobbied for the removal of EU interventionism on the basis of its distorting effect on international trade;
- EU sustainable development policies and initiatives;
- Pressure from NGO groups.

However, the primary incentive driving the EU CAP reforms was the unfeasible economics of production-based subsidies following enlargement of the Union. The twelve (2004-07) ascension countries would have more than doubled the number of EU subsidy claimants from 6.5 million farmers to 13.3 million. Romania's 4.9 million farmers alone were equivalent to 75 % of the existing EU-15 claimants, and the ratio of these nations' financial contributions to the EU fund, relative to the cost of subsidising their farmers, was completely untenable.

2.2 Housing

2.2.1 Materials

In comparison, the underlying factors forcing livestock farmers to find alternative bedding types are the same the world over: the closing of sawmills (Magner, 2008), and increased prices as competitive demand for by-products emerges (Marcinkowski and Adams, 2007). In contrast, the solutions are region-specific. Even within small communities, individual farmers may find different bedding types optimal for their particular *modus operandi*, based on climate, topography, cost and locality of available materials, livestock type, purpose and performance, and the intended use of the finished compost.

Marcinkowski and Adams (2007) provide a comprehensive, generic guide to the agronomic requirements of a bedding material:

- Comfortable for livestock to lie on
- Non-abrasive to the knees and hocks
- Non-slip, providing a sure footing when livestock recline and rise
- High in absorptive capacity for water and urine
- Low in initial levels of environmental bacteria
- Able to slow or inhibit bacterial growth
- Non-compactable and not dusty

- Easy to handle and maintain in stalls
- Inexpensive
- Safe for land application
- In constant supply

Bacterial content is of most concern to the 3,368 dairy holdings in Wales, owing to transfer via the teat canal, which causes mastitis. Rendos et al. (1975) compared the bacterial contents of a range of conventional bedding types used in temperate latitudes: namely, wheat straw, hardwood sawdust and hardwood shavings. Cows bedded on sawdust had the greatest teat-end populations of total coliforms and *Klebsiella*. *Streptococci* were most numerous on straw-bedded cows and *Staphylococci* were more numerous on both straw and sawdust-bedded cows compared to those on shavings. Rendos et al. proposed that the differences were related to the existing bacterial populations within the beddings. Given the biological and chemical similarities between hardwood sawdust and hardwood shavings, it is reasonable to extrapolate that the contrast in bacterial populations is a result of the bedding's physical structure, creating dissimilar micro-environmental conditions and that wood-based beddings made of larger particles - which allow greater airflow throughout and therefore lower humidity - offer a less favourable habitat for coliforms, *Klebsiella* and *Staphylococci*. However, Eberhart and Buckalew (1972) proposed that successful measures to exclude the common mastitogens, *Streptococcus agalactiae* and *Staphylococcus aureus*, merely opened a niche for more exotic mastitogenic bacterial species to succeed.

Cameron et al. (2004) presented a possible solution for dairy farmers. According to the report, the use of waste paper and paper pulp offers two significant benefits: greater absorbency than straw and a less suitable habitat for bacteria. In a study conducted at the University of Maine, Marcinkowski and Adams (2007) found the high (9.5) pH of a 'Fibre Mix' (a patent-pending combination of paper fibre, ash, clay fillers and lime), significantly limited bacterial growth in the bedding and on the cows' udders. In particular, the ash was found to inhibit the growth of coliform bacteria. He added, however, that paper-pulp fibre is often delivered very wet and requires considerable drying before use as cattle bedding; also, after bedding, it was heavy to handle without machinery. Conversely, shredded waste paper is not robust and putrefies when wet, thus large quantities are required to prevent the bedding becoming a slippery hazard to livestock. A collaborative study between DEFRA and the Open University, published in 2008, showed that the mean quantity of waste paper produced per household in 2007 was < 200 kg, of which > 95 % was recycled (Jones et al., 2008). Largely as a result of the Government's recycling schemes over the last decade, the quantity of waste paper available to farmers has been dramatically reduced, so in small rural communities, sustainable volumes for livestock bedding may simply not be available. In addition, farmers would presumably need to collect the material as efficiently as the local council's dedicated waste services to maintain the co-operation of any reluctant householders in the area. Ward et al. (2000) compared the chemical and physical properties of processed newspaper to wheat straw and wood shavings as animal bedding and found chopped or pelleted forms of newspaper and shavings had greater water holding capacities (> 400 %) than straw (200 %). They concluded that recycled newspaper was a viable bedding material, provided that source material is suitably processed for purpose and, critically, toxicity levels are low.

Zehnder et al. (2000) examined the use of municipal solid waste compost (MSWC) under cattle and found elevated concentrations of copper (Cu) in the kidneys, and lead (Pb) in both the liver and kidneys of the livestock at slaughter, although tissue concentrations of these elements were within a normal range for healthy cattle. They concluded that cattle bedded on MSWC were probably inhaling additional amounts of these elements from the bedding and excreting them through their faeces.

Bracken (*Pteridium aquilinum*) may offer a cheaper, more robust and absorbent alternative to straw bedding. It can be harvested using conventional balers in September, when the fronds have lower toxicity, but this material carries an enormous risk to animal health. It is the only higher plant known to have carcinogenic spores, as well as containing an array of toxins that cause conditions such as induced thiamine deficiency, acute haemorrhage syndrome, bright blindness, enzootic hematuria and upper alimentary carcinoma (Donnelly, 2003). Bracken also harbours ticks, particularly *Ixodes ricinus*, which is a known vector for the spirochaete responsible for causing Lyme disease (Page, 1997) and so should never be issued under young (< 1 yr) livestock.

Nevertheless, bracken has a long history in the UK. John Lightfoot's disgust for the fern was clear in his 1777 *Flora Scotica*, in which he suggests 'burning it, laying manure on it and urinating on it', presumably on separate occasions (Lightfoot, 1777). However, it is now understood that reforestation is a more effective, if not particularly agronomic method of eradication (Page, 1997). Bracken bedding is unpopular these days, but it has been used for centuries in Wales; in fact, if farmers have a sizeable bracken infestation on their land (which results in over-grazing of the remaining grassed area) cutting and harvesting the fronds is still one of the few agronomic control methods available. If bracken's toxicity can be mitigated, it could be a perfectly acceptable bedding material, as it can be stored outside when baled with little degradation, yet after housing, it decomposes quickly and carries a high nutrient value to land when applied as a fertiliser.

There are many accounts describing the use of woodchip in outdoor corrals (French et al., 2008), but none examining its specific use and performance under livestock in barns. A recurring and critical issue with outdoor woodchip corrals is excess leachate polluting the surrounding environment (McDonald et al., 2008). However, this issue is mitigated indoors, when dry woodchips (< 20 % moisture content) are used under sparse livestock densities on an appropriately constructed concrete base, with or without a run-off capture facility, as any free liquids are trapped long enough to be absorbed into the under layer of woodchips. Table 2.4 details the absorbency of a range traditional livestock bedding materials. Out-wintering on woodchip pads is discussed in greater detail in section 2.2.2.

Table 2.4: Type and absorbency of traditional bedding materials

Material	Type	Absorbency Factor*
Wheat straw	baled	2.1
	chopped	2.1
Barley straw	baled	2.0
	chopped	2.0
Oat straw	baled	2.5
	chopped	2.4
Hay	baled	3.0
	chopped	3.0
Sawdust	hardwood	1.5
	softwood	2.5
Shavings	hardwood	1.5
	softwood	2.0
Corn stover		2.5
Sand		0.3
Peat moss		10.0

* Weight of water held per unit weight of dry material; assumes initial moisture content of bedding < 10 %
Source - Ontario Ministry of Agriculture, Food and Rural Affairs, online

In 2006, ADAS Pwllpeiran ran a pilot project to test the agronomic viability of canary reed grass (*Phalaris arundinacea*) (CRG) under sheep, as a possible substitute for wheat straw bedding in Wales. They concluded CRG bedding did not affect the performance of sheep or present any additional health and welfare issues. Although the bedding costs for CRG at the time were 58 % higher than straw, the ex-farm price for both materials was around £40 /t. CRG is a forage crop that provides fibers for use in pulp and papermaking processes, but is predominantly grown as an energy crop, and can therefore be grown on set-aside land. However, it is difficult to envisage how the market forces needed to result in significant quantities of CRG being grown for bedding could occur, because if straw bedding prices were to increase owing to competitive demand from the bioenergy market, then they would do likewise for CRG. Furthermore, cereals yield two products with a diversity of markets and are therefore more agronomically viable to grow than CRG. However, it seems unlikely farmers would risk the expense of planting CRG without establishing potential returns from both markets, so the initial premise remains unchanged. In this context, the solution is to find a material that fulfils all of Marcinkowski and Adam's (2007) bedding requirements but has a low calorific value.

Panivivat et al. (2004) compared novel bedding materials, granite fines, sand and rice hulls to long wheat straw and wood shavings, beneath sixty dairy heifers. In summary, they found the growth performance and dry matter intake did not differ across the five bedding types, although calves housed on granite fines and sand were treated more often for scours and calves housed on straw received the fewest antibiotic treatments. Granite fines formed a harder surface than other beddings, and calves housed on fines and sand were dirtier than those on biotic beddings. Straw had the warmest surface temperature; rice hulls and shavings were warmer than granite fines and sand. Faecal coliform counts were greatest in rice hulls before bedding, but in straw beds after bedding, when straw also had the lowest concentration of ammonia at 10 cm above the surface. Many studies have shown that the great advantage of abiotic beddings is that they are inhospitable to mastogenic bacteria (Zdanowicz et al., 2004) and even *E. coli* O157:H7 (Westphal et al., 2011). However, Justice-Allen et al. (2010) proposed that recycled bedding sand could be an environmental source of *Mycoplasma spp*. (including *M. bovis*) infections in dairy cows, albeit from a non-comparative bedding study.

Many regions around the world are currently investigating alternative bedding types as government legislation dictates a plethora of market responses to climate change. The overarching solution that emerges is one of 'whatever is regionally appropriate' in terms of soil requirements (finished product nutrient values), regional climate and livestock purpose. For example, sand seems to be successful in Maryland and Maine, so long as the damp sand doesn't freeze at night. Bracken is a possible alternative to straw in Wales, but not under young livestock (< 1yr old) and with strict controls; likewise paper, if sufficient quantities of non-toxic material are available, and CRG if market mechanisms promote its availability. Woodchip (the larger cut the better) is good for abating mastitogens in dairy barns. However, straw's versatility, absorbency and degradability means it will remain the totemic livestock bedding material in temperate regions (Olson, 1940), if price allows.

2.2.2 Systems

Housing systems are governed by livestock type, bedding material and the particular layout and operating capabilities of an individual farm's facilities and machinery. For example, in the UK it is a fairly common practice with cattle not to put bedding where the livestock stand to feed, owing to their propensity to defecate and urinate while eating. The slurry from this feeding area can be easily collected and stored, then reintroduced to the bedding after housing to accelerate decomposition or left to mature before being applied directly to land. However, while using a scraped area requires less bedding during the housing period, it is generally more labour intensive to maintain, than for example, deep litter systems, where an initial layer of bedding is topped up periodically (Kapuinen, 2001). There is myriad of system refinements that have been developed by farmers, under the confines of their own facilities, but this section will focus on the generic, comparative use of woodchip under livestock in outdoor corrals and indoor pens over winter.

The concept of using woodchip in outdoor corrals (OWC) to over-winter livestock, originated in New Zealand (Smith et al., 2005) during the early 1990s, as a low cost means of husbandry without expensive buildings. It has since been adopted in temperate regions around the world, including Canada (Larney et al., 2008), Scandinavia (Manninen et al., 2008), France (Menard et al., 2010) and the UK. Corrals can either be lined with plastic sheeting or unlined (Dumont et al., 2010). The key problem with unlined corrals is the vertical and horizontal diffusion of leachate entering and polluting the surrounding land and watercourses (Morse-Meyer et al., 1997; Miller et al., 2006; Vinten et al., 2006); The UK's *Code Of Good Agricultural Practice* (CoGAP, 2009) does not give specific direction on the positioning of OWCs, but implies through its instructions on storage of agricultural waste that corrals should be at least 50 m away from a watercourse, spring, well, borehole or any source of drinking water, and at least 10 m from any land drains and vulnerable groundwater (IGER, 2007) principally to prevent contamination from the spread of protozoans (*Cryptosporidium* and *Giardia*). McDonald et al. (2008) examined the leachate volume and nutrient flow from four dissimilar OWC's in Scotland and found significant flows of leachate occurred on most days during a 1-year sampling period, and that leachate volumes increased with stocking density. Their conclusions indicated that corral development is worthy of specific regulatory attention, which does not currently exist. This recommendation is echoed in the majority of government-funded and academic-based projects in England and Wales (Smith et al., 2005), Ireland (French et al., 2008; French and Hickey, 2004) and in Scotland (Vinten et al., 2006).

A waning tradition in Scandinavia and parts of northern and eastern Europe is to use tree pollards as both a source of leaf fodder and bedding. Wooded meadows were pollarded in August; the leafy branches cut into manageable lengths and tied together using hazel (*Corylus avellana*) or birch

(*Betula*) twigs, so that they could be easily carried. They were then hung on racks, in trees or on fences to dry, before being fed to the livestock in barns over winter. The animals ate both the leaves and the bark, after which the farmers burnt the remaining twigs for fuel (Read, 2008).

2.2.3 Livestock performance

A wide range of research has been undertaken on the impacts on livestock welfare, performance and behaviour, under various housing conditions. Kossaibati and Esslemont (1997) estimated that production diseases and other health problems in an average dairy herd in England are dominated by mastitis (38 %) and lameness (27 %). Both these conditions are, in varying measure, a product of bedding type, housing system and floor texture. Eberhart and Buckalew (1972) showed incidences in which efforts made to exclude the two most common mastogenic bacteria, *Streptococcus agalactiae* and *Staphylococcus aureus*, from the bedding matrix simply opened up the niche to other species. Rendos at al. (1975) compared the anti-bacterial performance of sawdust, wood shavings and wheat straw beddings and suggested the inherent environmental properties of sawdust and straw supported more common mastogenic bacteria than shavings. Faecal coliforms and *Klebsiella* were prevalent in sawdust, *Streptococci* in straw and *Staphylococci* in both sawdust and straw when compared to numbers of colony forming units (CFU) in shavings. In general, higher incidences of lameness have been found in herds housed on unyielding floor surfaces without sufficient bedding (Singh et al., 1993; Webster, 2002; Barker et al., 2007; Norring et al., 2010).

Higgins and Dodd (1989) assessed out-wintered animal performance in six locations around Scotland. Their results showed an average weight loss ranging from 24 to 73 kg for out-wintered steers (100 kg initial weight), on a projected gain of 0.75 kg/day, when compared with the performance of housed steers. In contrast, Hickey et al. (2002) found that, 126 Charolais-Friesian steers (474 kg mean initial weight), accommodated on outdoor woodchip pads (OWPs) had a higher daily live-weight gain, carcass gain and food intake, and lower fat scores, per 100 kg carcass than animals housed on indoor slats. Furthermore, neither the provision of wind shelter nor an increased space allowance within OWP treatments delivered any significant increase in the steers' growth or energy efficiency, and there was no physiological or behavioural evidence to suggest the subjects required wind shelter, or were distressed by out-wintering. The study also found that woodchip provided the animals more security during the standing/lying mechanism than slats, and animals accommodated on OWPs had a lower severity of hoof under-run and white line disease, but suffered more severe heel erosion, at low stocking densities.

French and Hickey (2004) followed up their earlier research by investigating the attributable influence of the environment (indoor vs. outdoor), space allowance and surface type (slat vs. woodchip), on the animals' intake and performance. Animals housed outdoors on woodchip at a low stocking density of 10.8 m^2 had higher growth rates (0.35 %) than those on indoor slats with 2.7 m^2 /animal. They concluded that 60 % of the advantage was attributable to increasing the space allowance from 2.7 m^2 to 10.8 m^2 on slats, while the remainder was due to a softer lying surface provided by woodchips. However, they went on to state there was no productive advantage *per se* in accommodating animals outdoors rather than indoors.

In a recent study, Dumont et al. (2012) tested livestock performance on OWPs based on woodchip size, feeding management and area allowance. The study used a Greco-Latin square experimental design and divided thirty-four, 18-month-old Charolais/Friesian steers (average weight 470 kg) into four groups, which were randomly rotated around OWPs containing four woodchip (Douglas Fir) sizes: (i) an irregular-shaped flat 5 cm to 10 cm woodchip (similar to the ADAS W53 chips used in the present study); (ii) a long-shape woodchip 2 cm to 4 cm; (iii) a cubic-shape woodchip 1 cm to 2 cm (similar to the ADAS W34 andW55) and (iv) sawdust 0.1 cm to 1 cm. Feed management meant cattle were fed silage either from a concrete feed area in front of the OWP, or from the surface of the OWP itself. Area allowances included: 11.1, 11.8, 14 and 18.6 m^2 $steer^{-1}$. The study found no significant differences in silage intakes between experimental treatments, although daily live-weight gain (DLWG) was greatest on the fine sawdust bedding, and least on the large irregularly shaped 5 – 10 cm woodchips.

Menard et al. (2010) carried out an extensive study over four years in Brittany, France, designed to assess the comparative efficacy of woodchip and straw on OWP through the accumulative analyses of animal performance (milk yield, growth), hygiene (cleanliness, mastitis, quality of milk) and welfare (injuries, lameness, human-animal relationship); in addition, the study was designed to characterise the effluents released. Primarily, they concluded OWP are suitable for dry cows and heifers, but not lactating cows.

Dunne et al. (2008) compared the meat colour, composition and eating quality of 45 Charolais steers accommodated in OWPs stocked at 18 m^2 /head, indoors on slatted floor pens at 2.5 m^2 /500 kg bodyweight and in straw-bedded pens at 4 m^2 /head, for 132 days. Although mean carcass weights were 372, 351 kg and 362 kg respectively, they concluded that accommodating cattle on OWP had no significant lasting effect on meat colour and no impact on composition or eating quality.

Von-Keyserlingk et al. (2008), supported the findings of (Hickey et al, 2002) that floor hardness and bedding depth were the determining causes of lesions, lameness and hoof disease during housing and added that greater space allowances enhanced cattle performance by reducing competitiveness in the feed and lying areas, suggesting that partitioned feed gates would reduce the bullying of socially subordinate animals by dominant herd members. There is broad consensus that stocking density is a critical factor in livestock performance. Gonyou et al. (1985) found that feeder lambs, at a density of 0.32 m^2 vs. 0.48 m^2 / lamb, underperformed by 1.5 kg /lamb (10 %) and Randolph et al. (1981), reported decreases in swine performance at high stocking densities; 0.33 m^2 (vs. 0.66 m^2 /pig) resulted in a reduced daily gain of 44 g /day (6.8 %) and a less efficient feed/gain ratio of 2.47 vs. 2.39. Furthermore, the same study observed an increase in aggressive behaviour within the high-density pig pens, but added that the data showed no consistent correlation between performance and levels of aggression or type of activity.

The behavioural preferences of cattle to base and bedding types have been studied in some detail. Hacker et al. (1969) tested two mattress types, rubber and synthetic resin, with five base types: electrically heated concrete (mean temperature 18° C); standard concrete with 1.3 cm plywood cushion between the mat and the base; Zonolite insulated concrete; 1.3 cm plywood sheet on a wooden frame; and, lastly, standard concrete. The time cattle spent lying on each treatment was recorded over two winters and revealed their conclusive preference ($p < 0.01$) for synthetic resin mats over rubber and for the electrically heated concrete base ($p < 0.01$) over the other four bases. Keys et al. (1976) conducted a ‘free choice’ experiment, to test cattle preference to three bedding types: dewatered manure solids (DwMS) (29 % dry matter); dehydrated manure solids (DhMS) (90 % dry matter); and sawdust (81 % dry matter). During winter, cattle spent an average of 0.5, 6.6, and 6.2 hrs /day respectively lying on each bedding type, and 0.5, 3.4, and 2.0 hrs /day during the summer. The trial demonstrated cattle’s preference for dry bedding; however, the relative cost of producing sufficient material to fill one stall 10 cm deep was $2.63 for DwMS, $11.46 for DhMS and $1.27 for sawdust. Equivalent bedding production costs could not be determined, so the article’s (now dated) prices are included as a guide. Similarly, Reich et al. (2010) demonstrated cattle’s preference for drier bedding through a trial involving five groups of three non-lactating Holstein cows on five sawdust beddings with systematically varying moisture contents, conducted in both summer and winter. Average lying time was 10.4 ± 0.4 h/d on the wettest treatment, compared to 11.5 ± 0.4 h/d on the driest, and 12.1 +/- 0.4 h/d in winter compared to 9.9 +/- 0.6 h/d during the summer. However, they found no correlation between season and bedding dry matter.

More recently, Norring et al. (2010) concluded that comfort is a discernible priority to cattle, following a study of 18 cows using three stall surface materials (concrete, soft rubber matting, and sand). Where no choice of bedding was given, lying times were longest on the rubber mats compared to other surfaces (rubber mat, 768 mins /d; concrete, 727 mins /d; sand, 707 mins /d (all treatments ± se 16 mins/d)). Where a choice of two out of three surfaces was available the cattle again preferred rubber mats to stalls with a concrete floor (median 73 vs. 18 from a total of 160 observations per day), but showed no preference for sand compared with a concrete floor or rubber mats.

By now it will be apparent that sheep are less commonly used as case studies in housing trials than cattle, so the report by Wolf et al. (2010) on 64 Suffolk x Mule (Blue-faced Leicester x Welsh Speckled Face) and 64 Charolais x Mule lambs is interesting, particularly as it mirrors this study in comparing woodchip and straw beddings. Their results showed that lambs used woodchip as a bedding material when lying or standing almost twice as often as straw ($p < 0.001$), but showed no preference between bedding types when eating hay or concentrates ($p > 0.05$). Furthermore, there was no significant effect based on sex, which day the lambs were observed, whether the lambs had prior experience of the bedding materials, on their preference for woodchip (all ($p > 0.05$)). Wolf et al. (2010) concluded that woodchip is a suitable alternative bedding material to straw and is unlikely to affect the lambs' performance through changes in the proportion of time spent lying, standing or eating.

Perhaps unsurprisingly, these behavioural studies all show that livestock prefer warm, dry and cushioned housing conditions. This isn't a luxury, as inadequate housing systems have repeatedly been shown to adversely affect the health (Webster, 2002), welfare (Singh et al., 1993; Endres and Barberg, 2007) and therefore the productivity of all types of livestock (Randolph et al., 1981; Gonyou et al., 1985; Kossaibati and Esslemont, 1997; Kiernan et al., 2003; French and Hickey, 2004; Von-Keyserlingk et al., 2008; Hill et al., 2011).

2.2.4 Sanitization by composting

A critical question investigated by the present project was whether the woodchip bedding could sustain high enough composting temperatures to eliminate the pathogens *Escherichia coli* and *Salmonella enterica* so it could be safely re-used as bedding each winter, until the material is fully degraded and ready for land spreading (section 2.3.2, below).

Cattle are the primary reservoir of *Escherichia coli* (*E. coli*) serotype O157:H7 (Wells et al., 1991), but the prevalence of faecal shedders is usually less than 1 % of the herd, estimated to be between 3 – 50,000 CFU /g of faeces. However, the infective dose for humans is only about 10^1 CFU /g; the lowest of all the common human food-borne pathogens (Kirk, 2003). Fortunately, *E. coli* O157 does not persist for long periods in the farm environment, particularly within abiotic livestock beddings (Westphal et al., 2011), but can grow under conditions normally considered adverse to bacteria (Himathongkham et al., 1999). However, Larney et al. (2003) reported that > 99.9 % of total coliforms were eliminated within the first seven days of composting animal wastes at mesophilic temperatures between 33.5 to 41° C, well below the baseline thermal kill limit of 55° C stated in the US and Canadian composting guidelines (USEPA, 2003; Canadian Council of Ministers of the Environment, 2000) and the 65° C for 7 days required by the UK (PAS100). Furthermore, research by Kumar and Sekaran (2005) reported that vermicomposting reduced *Salmonella* and *E. coli* counts to nil after 60 days in compost material, and after 70 days from within the earthworms' guts. Regardless of the composting method, during the first 2-5 weeks of composting, wastes and liquid runoff should be contained to prevent seepage of bacteria into ground water.

The UK PAS100 regulatory standards require that composts reach > 65° C for a minimum of seven days (not necessarily consecutively), to be deemed sanitized. Legislation governing the re-use of woodchip-manure compost requires that:

- It does not endanger human, animal or environmental health - PAS 100 composting standards.
- *'The animals have dry areas to lie down'* (Schedule 1 of the Welfare of Farmed Livestock (Wales) Regulations 2007, paragraph 13 and 17 in particular) – if the compost has met PAS100 temperature requirements and has not subsequently been watered or subjected to high levels of rainfall, it is reasonable to expect the moisture content will be sufficiently low to provide dry bedding the following winter.
- '*The composted woodchip does not contain high levels of dust, noxious gases or spores etc.'* After seven months' composting of typical agricultural feedstocks and conditions, levels of dust, noxious gases and spores within the woodchip manure should not present a hazard, although tests should be carried out if in any doubt.

Tiquia et al. (1998) questioned the efficacy of windrows in eliminating faecal *Streptococci*. In particular, the cooler areas at the outer edges of the windrows could potentially reduce efficiency in the sanitisation process. However, regular mixing of well-managed windrow composts ensures that virtually all the material is subjected to temperatures above 55° C. Kirk (2003) also identified the environmental parameters critical to pathogen survival as:

- Type of slurry or manure
- pH

- Moisture content
- Temperature
- Abundance and diversity of microbes within the compost environment.

In a recent and extensive study of six Belgian dairy herds, Verbist et al. (2011), found that *Klebsiella pneumoniae* can be prevalent within the livestock's immediate environment (faeces, and in this case, used sawdust bedding), without causing significant mastitis problems, and confirmed unused sawdust bedding was not an important source of the species. Carroll and Jasper (1978) investigated the distribution of *Enterobacteriaceae* in recycled cattle manure bedding, and their findings supported these environmental control mechanisms. Contrary to Verbist et al. (2011), they reported *Klebsiella* were not common in bovine faeces, but went on to state that the composting process effectively reduced coliform counts to, or near to, zero. This is particularly encouraging when considered in conjunction with evidence presented by Rendos et al. (1975), who showed that hardwood shavings (bulky, porous, potentially low humidity) supported significantly fewer *Enterobacteriaceae* and *Staphylococci* CFUs than hardwood sawdust (compact, reduced airflow, greater humidity), implying that large particulate, ligneous beddings offer pathogens a sub-optimal environment. Furthermore, Carroll and Jasper (1978) added that if the compost moisture content increases and temperature drops, coliforms return in large numbers. They concluded that composted cattle manure was a satisfactory bedding material, provided it was dried properly before application, but they did not state the specific moisture content. Although, as Keys et al. (1976) showed, the cost of dehydrating manure solids to 90 % dry matter is not economically viable, so it is perhaps fortunate that this criterion is not stipulated in the UK PAS100.

2.3 Composting

2.3.1 Benefits of composting within the farm environment

Nutrients can be seen as the base currency of every farm system; production removes them, and (often expensive) fertilisers are used to replace them. To maximise efficiency, producers must ensure that nutrients that don't go to market in crops and livestock, but are retained and recycled on the farm. One important method of maintaining nutrient balance within a livestock system is composting the winter bedding, and thereby recycling organic wastes into fertiliser.

Nitrogen retention is the primary focus of agricultural composting because of its criticality to production and its high loss potential. The speed and efficiency of composting is largely dependent on the feedstock's physical and chemical properties; total and available carbon to nitrogen (C:N) ratio; surface area; oxygen levels and moisture content.

2.3.2 Composting process and nutrient dynamics

Microbes require C, N, phosphorus (P) and potassium (K) for growth, but also use N for protein synthesis and oxidize C for energy, generating heat and releasing CO_2 (Sweeten and Auvermann, 2008). As a result, more C than N is required. Misra et al., (2003) state that while C:N ratios between 20 and 40:1 are acceptable, 25 to 30:1 are optimal for composting. Similarly, Bernal et al. (2009) proposed a C:N ratio for composting in the range of 25 to 35:1, adding that C:N ratios of less than 20:1 are prone to excess N losses. This was corroborated by Kuo et al. (2004), that reported C:N ratios greater than 40:1 result in limited microbial growth and longer composting time. Michel et al. (2004) reported that less than 10 % of N was lost when C:N ratios were greater than 40:1 during dairy manure composting amended with straw sawdust and sand. However, these ratios broadly represent the consensus, with minor deviations depending on feedstocks. Eiland et al. (2001) successfully composted a mixture of miscanthus straw and pig manure with initial C:N ratios of 25:1 and 16:1 and Zhu (2007) concluded that an initial C:N ratio of 20:1 was more efficient than 25:1 when composting pig manure with rice straw. Further, Calderón et al. (2004) showed that N mineralization is related to the C:N ratio of manures, reporting that a ratio of 19:1 resulted in negative N mineralization while manures with an average C:N ratio of 16:1 had positive N mineralization. However, Eghball et al. (2002) proposed that the availability of C and N in manure was more important than the general C:N ratio, which is supported by findings in the present study where ratios of available C to available N in the woodchip composts were never greater than 10:1, due to very low concentrations of both DOC and TSN.

As mentioned previously, compost bulk density (related to porosity and particle surface area), nutrient content (especially availability of C and N) temperature, pH, moisture and supply of O together determine the speed and efficiency of decomposition. Aerobic decomposition takes place on particle surfaces in the presence of O_2, so smaller compost solids allow faster rates of microbial digestion and reproduction, and greater heat generation. However, very fine material may compact, restricting airflow, leading to anaerobic conditions that generate malodorous and harmful emissions of hydrogen sulphide (H_2S) (Hagenstein et al., 2003), methane (CH_4), denitrification products, nitrogen oxide (N_2O) and nitrogen gas (N_2) (Moral et al., 2012), as well as ammonia (NH_3).

Ammonia volatilization is a surface process accelerated by airflow (Misselbrook et al., 2001; Gilhespy et al., 2009; Dumont et al., 2012), so the large bulky woodchips, with less surface area, potentially reduce NH_3 loss. However this benefit is counteracted by their rigid shape, which maintains porosity and airflow. Conversely, straw bedding has a large surface area and greater absorbency capacity by weight, but less structural rigidity, which potentially restricts airflow. Soiled straw bedding has a low lignin content and high levels of AC and AN in optimal ratio for microbial metabolism, reproduction, and thus decomposition and nitrification. High compost temperatures generate convection currents that draw in fresh O and drive off water vapour, CO_2 and NH_3. Turning the compost frequently helps maintain O levels, especially in less rigid compost structures, and brings new material into contact with microbes, but also releases previously trapped NH_3. Moisture content is critical as microbes can only use chemicals in solution on particle surfaces. According to Misra et al. (2003) compost moisture content should be between 50 and 60 % at the start of composting and reduced to 30 % by the end. Excess moisture or even water-logging will cause an increase in nutrient run-off, inhibit microbial function and reduce oxygen diffusion throughout the compost. If the compost becomes anaerobic after nitrification has occurred, then NO_3^- is denitrified to N_2O or N_2 and lost to the atmosphere (Bernal et al., 2009).

The heat that microbes generate within the compost is an important measureable response to the initial chemical and physical conditions. The initial temperature increment is dominated by three bacterial groups. Psychrophilic bacteria colonize the compost between 0 and 22° C, as the compost warms up; conditions favour mesophilic (middle range) bacteria, which thrive at 10 to 45° C; multiplying rapidly on readily available sugars and amino acids, their activity increases the temperature beyond their tolerance and they are succeeded by thermophilic bacteria with an optimal temperature range of 40 to 60° C (Rynk, 1992), although Bernal (2009) narrows this range to between 52 and 60° C. The thermophilic phase is important for the quality of the compost, as pathogens are normally eliminated at and above 55° C and weed seeds at 62° C (Misra et al., 2003). Thermophilic microbial activity requires depleted O to be replaced, or conditions will rapidly become anaerobic. During the early active phase of composting, large amounts of urea N is hydrolysed into NH_4^+ then mineralised, which increases compost pH. However, at pH >8.5 ammonium dissociates into NH_3 and CO_2. Martins and Dewes (1992) found that as much as 55 % of total N loss could be volatized as NH_3 during the thermophilic phase; immobilized, if sufficient AC is present; or nitrified, depending on the composting stage and characteristics of the pile. Zvomuya et al. (2005) suggested reducing NH_3 volatilization using phosphogypsum, an acidic by-product of P fertiliser manufacture in Canada and America, but the technique carries risks: phosphogypsum contains trace concentrations of radium.

2.3.3 Value of compost as organic fertiliser

The most significant benefits of applying compost to soils - as opposed to chemical fertilisers - are its long-term benefits to soil health and nutrition. Compost is a rich source of organic matter (SOM), important in sustaining soil fertility and, hence, in sustainable agricultural production. In addition to being a potential source of plant nutrients on decomposition (e.g. if it contains proteins), it improves the physical, chemical and biological properties of the soil (Bernal et al., 2009).

2.3.3.1 Physical properties

According to Werner (1997), compost improves soil physical properties by lowering bulk density and thus increasing pore space and aeration, generating a more favourable environment for biological activity. In addition, compost increases the soil's water holding capacity (Shiralipour et al., 1992) by improving infiltration (Butler and Muir, 2006). Conversely, soil in poor physical condition is linked to a decline in crop performance and profitability, as well erosion and nutrient leaching into surface and ground waters (Kuo et al., 2004).

2.3.3.2 Chemical properties

Alvarez et al. (1988) showed a positive correlation between SOM content and levels of available Ca, K, Mg, Na, and P, in addition to increasing total soil N. Furthermore, Wong et al. (1999) showed that manure compost can be used to restoring soils whole nutrient balance, as it increases the concentration of macro- and micro-nutrients available for plant growth.

2.3.3.3 Biological properties

The findings of Wong et al. (1999) were supported by Das and Dkhar (2011), who reported that organic fertilisers enhanced soil microbial populations and increased rhizosphere soil physicochemical properties compared with application of inorganic NPK fertiliser. In addition, Wander et al. (1994) found that organic farming systems (which are characterised by the application of compost, or compost-like organic materials) support higher levels of microbial diversity and activity than conventional systems using inorganic fertilisers.

As compost is applied to the soil, over time an active nutrient cycling capacity will be developed, based on a diverse and healthy microbial community. This will increase the rate at which nutrients are made available for crop uptake. These advantages can be anticipated to reduce cropping risks, increase yields and provide cost savings from reduction in use of inorganic fertiliser.

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3.1 Introduction

The Welsh Government (WG) has forecast a significant reduction in the availability of straw bedding to the UK agricultural livestock sector. This has arisen due to increasing demand for straw within the expanding biofuels industry. This loss of straw from the agricultural sector will particularly impact Welsh farmers, especially if coupled with rising fuel prices and therefore haulage costs, as Wales's topography and primary soil type does not allow sufficient cereal production to satisfy the nation's livestock bedding requirements. In light of these combined pressures, WG commissioned the Woodchip for Livestock Bedding Project to investigate the feasibility of woodchip as an alternative source of livestock bedding, with specific emphasis on its long-term environmental and economic sustainability.

There are a variety of locally-sourced materials suitable for livestock bedding available to farmers in different regions of Wales. However, straw is currently the most popular and is estimated to cost the nation's farming industry £12.5m per annum. In comparison, wood represents an abundant national resource, with significant residues coming from both the forestry and furniture manufacturing industries. In addition, interest in the use of locally sourced products is gaining momentum and an emerging woodchip agric-bedding industry could take advantage of the infrastructural developments initiated by growth in the use of woodchip as an alternative, renewable, domestic heating fuel.

To date, many studies have investigated the use of outdoor winter corrals, within which woodchips are used as a base material (Dumont et al., 2010; Larney et al., 2008a and 2006; Hickey et al., 2002), but none have yet specifically examined the practical and environmental benefits of using woodchip as an indoor bedding material. Based on this knowledge gap, woodchip housing trials were conducted with sheep and cattle over an eight week period. Overall, these trials sought to develop practical recommendations for the optimal use of woodchip bedding and assess its composting performance and potential reuse as bedding material. Additionally, these studies sought to elucidate a broader understanding of the nutrient dynamics and temporal changes in the material's physical characteristics. The aim was to relate these observed changes to agronomic and environmental priorities. In this context, an emphasis was placed on the fate of nitrogen throughout the bedding and composting process.

Trial 1 (hereafter referred to as the ADAS trial) sought to investigate and compare the influence of initial woodchip moisture content on the woodchip bedding's efficiency and subsequent composting efficiency. The hypothesis was that woodchip with lower moisture content would have a greater capacity to absorb fluid and incorporate solid wastes throughout the litter layer, thereby increasing the time between fresh bedding applications (i.e., promoting increased resource use efficiency). In order to better understand the material's absorbency capacity, two separate experiments were carried out to assess the absorbency rate and capacity of woodchips with different moisture contents. A full description of these experiments is presented in Appendix I, and key points are highlighted in this chapter's results section. In addition, the impact of woodchip moisture content was also investigated in terms of its end use in composting and the resultant compost quality. Throughout the trials direct comparison was made with conventional straw bedding practices. Trial 2 (hereafter referred to as the IGER trial) investigated the effect of a dry hay diet against that of a wetter silage diet on the performance of woodchip and straw bedding and subsequent compost. Performance was defined by whether the quantity or frequency (and thus, material and labour costs) of fresh bedding applications increased in silage fed pens to maintain a standard level of livestock performance (scored on animal weight gain, feed intake, health, respiratory problems, cleanliness score and welfare). It was hypothesized that woodchip under the wetter silage diets would be used less efficiently, due to increased quantities of liquid excrement compared to the hay diets; conversely composting performance of silage/woodchip would be enhanced due to greater quantities of available C and N. While bedding, manure and composting findings are presented here, the livestock's health and welfare were outside the scope of this project.

Presentation of results

Where applicable, results are presented on a dry matter (DM) basis, unless clearly stated otherwise (wet weight (WW and w/w) or fresh weight (FW)). Results of the housing and composting trials are presented in the order of physical and then chemical dynamics, as opposed to chronological order (housing then composting); because of the sheer volume of chemical analyses carried out and reported, the candidate considered that it would be of greater benefit to the reader to have a continuous compendium of chemical results, albeit at the cost of having to refer back to the physical results.

3.2 Method

3.2.1 Study design

Housing protocols at the two trial sites were not linked, so no statistical comparisons can be drawn between the ADAS and IGER results. In addition, there were aspects of both sites' protocols that could have been altered to facilitate more accurate and in-depth analysis of the results.

Table 3.1: Dates and duration of housing trials at ADAS and IGER

Housing periods		Start	Finish	Duration
ADAS	Sheep	20-Jan-06	17-Mar-06	8 wks.
ADAS	Cattle	03-Feb-06	31-Mar-06	8 wks.
IGER	Sheep and Cattle	25-Jan-06	23-Mar-06	8 wks.

Source of woodchip and straw

The woodchip used at both sites was sourced from Coed Fron Goch sawmill, Trisant, near Aberystwyth (52°21'45"N, 3°53'19"W). Chipping was done prior to delivery at the trial sites, using a Heizohack HM8-400 drum wood chipper (Heizohack GmbH, Gunzenhausen, D-91710 Germany). Although the ADAS W53 and W55 woodchips had similar initial moisture contents, the W53 woodchip bedding was produced from fencing post points, which resulted in a bias towards large, flat, splinter shaped woodchips (Plate 3.1), ranging from 5 – 10 cm long and 1 – 3 cm wide, but only 0.5 – 1.5 cm thick, compared to the W55 (and W34) stocks, which were chipped from rounds and gave a square, 'chunky' chip (approximately 1 – 3 cm cubed) even though the same make and model of chipper was used (Plate 3.2). Furthermore, it suggested fence post 'points' are essentially made from the centre of the bough, and therefore contain predominantly older, denser wood than wood chipped from rounds, which must contain heterogeneously aged material. This has proved to be an important factor and will be discussed in subsequent sections.

There were two woodchip deliveries used at IGER over the course of the study. The first one was used in weeks 1-5 of the housing trial and the second in weeks 6-8 inclusive. Due to the physical and chemical similarity of the two woodchip stocks (see Table 3.43), no further differentiation between the stocks is necessary. Wheat straw at ADAS and IGER was locally sourced. However, due to limited availability, ADAS wheat straw was supplemented with barley straw. Given time constraints and volume of prerequisite analyses for HCC, it was beyond the scope of this project to investigate the extent this protocol anomaly may have had on the results.

3.2.1.1 ADAS: Study Design

ADAS Pwllpeiran is the UK's largest independent provider of environmental consultancy, rural development services and policy advice, and as such was well placed as a project partner to provide services, input, manpower, experimental space and importantly, livestock. Two studies were undertaken at the ADAS Pwllpeiran station located at Cwmystwyth, Ceredigion, UK (52°21'19"N, 3°48'02"W). The design of the two livestock studies ran in parallel, one with pregnant ewes and the other with yearling Welsh Black cattle. Both studies lasted 8 weeks and consisted of 4 treatment pens and 3 woodchips with initial moisture contents of 34.4 %, 52.7 % and 54.9 %, alongside a conventional straw-based treatment. For the purposes of this paper the three woodchip bedding types will be referred to as W34, W53 and W55 respectively: or S34, S53, S55 (sheep-woodchip treatments) and C34, C53, C55 (cattle-woodchip treatments) when referring to individual compost treatments.

ADAS Cattle study

The cattle housing trial ran from 3rd February until 31st March 2006. Thirty two one-year-old Welsh Black cattle were divided equally into four groups (balanced for age, sex, weight and cleanliness) and housed in an open-fronted shed. Each group (n = 8) was housed in separate pens measuring 4.3 m x 10.6 m. Group 1 was housed on straw (control: moisture content 11 %), Group 2 was housed on W34 moisture (w/w) woodchip, Group 3 was housed on W53 moisture (w/w) woodchip and Group 4 was housed on W55 moisture (w/w) woodchip. Owing to limitations in the design of the study (which were beyond the control of Bangor University), the treatment pens were only singularly replicated. Ideally, a replication rate of three or greater would have been desirable for a study of this kind.

Silage was fed *ad libitum* and 2 kg head^{-1} day^{-1} of concentrates offered at a single front-facing feeding station (see Table 3.5). Standing areas behind the feed face were regularly scraped clean and the manure removed, but not reintroduced before composting. All pens were bedded to an initial depth of 100 mm. To maintain housing and animal cleanliness, additional bedding material was applied when livestock showed signs of clagging. Table 3.3 provides details on the size, area allowance and livestock number pen^{-1}, as well as the total dry matter (DM) and moisture content (MC; %) of beddings deployed pen^{-1} throughout the eight week housing period. At the end of the study, all bedding material was chemically and physically characterised and subsequently composted.

ADAS Sheep study

Notably, the 8 week ADAS sheep housing trial ran from 20th January until 17th March 2006, so concluded two weeks prior to the cattle housing trial. However, ADAS started composting them the same day, resulting in the 4 sheep treatments being constantly two weeks older than the respective cattle treatments throughout the composting trial which concluded on 4th November 2006, when the cattle compost treatments were 31 weeks old and the sheep compost treatments were 33 weeks old. The ADAS sheep housing trial consisted of 120 twin-bearing ewes in mid gestation divided equally into four groups (balanced for age, sex, weight and cleanliness) and housed in a purpose-built experimental sheep shed. Each group (n = 30) was housed in its own pen within the sheep shed measuring 6.7 m x 4.6 m; Group 1 was bedded on straw (control: moisture content 11 %), Group 2 on W34 moisture woodchip, Group 3 on W53 moisture woodchip and Group 4 on W55 moisture woodchip. Silage was offered to the sheep ad libitum from a single feeding face at the front of the pen. EweMaster® 18 % protein sheep pellets (concentrate) were fed at a rate of 500 g head^{-1} d^{-1} in troughs at the side of each pen (see Table 3.5).

At the start of the trial, all pens were bedded to a depth of 100 mm. To maintain housing and animal cleanliness, additional bedding material was applied as a top-up layer as and when required. Table 3.3 provides details on the size, area allowance and livestock number pen^{-1}, as well as the total DM and MC (%) of beddings deployed pen^{-1} throughout the eight week housing period, after which all bedding material was chemically and physically characterised.

ADAS protocol anomalies: Bedding types and moisture contents

The trial's aim was to facilitate robust analysis of the effect initial moisture content had on the bedding and composting performance of woodchip. In order to determine with confidence that observed differences in the results were due to the woodchip's initial moisture content, it was agreed that woodchip stocks with three moisture contents would be tested: 20 %, 40 % and 60 %. However, there was insufficient time for ADAS to achieve these moisture contents prior to the start of the housing, so the trial commenced with initial woodchip moisture contents of 34.4 %, 52.7 % and 54.9 %. In addition, each livestock trial included a straw treatment. ADAS started the trials using wheat straw, but switched to barley straw because they were unable to procure any more wheat straw.

Different ages of livestock composts

It is understood that ADAS wanted their sheep (pregnant ewes) turned out one month before they lambed in mid-April. As such, they conducted their eight week sheep housing trial two weeks earlier than the cattle trial. After releasing the sheep, the bedding was moved from the purpose-built sheep shed to the barn the cattle were still housed in, where it was set in pyramidal piles to begin composting. Two weeks later the cattle were turned out and the beddings also set in pyramidal piles. It was at this point the candidate's PhD programme at Bangor began. So the first samples collected from the sheep-based composts were 15 days old and the cattle-based composts were 1 day old.

Manure handling

Different volumes of water were added to compost treatments during the first 2 months composting when ADAS considered they were becoming too dry. Table 3.2 shows water was added to all three sheep-woodchip treatments and the cattle W34 % treatment.

Table 3.2: Volumes of water added to a range of woodchip composts at ADAS

Treatment	Composting week	Volume (litre)
Sheep 34 %	Wk. 3	148
	Wk. 5	230
Total (ltrs)		**378**
Sheep 53 %	Wk.5	55
	Wk.7	70
Total (ltrs)		**125**
Sheep 55 %	Wk.5	123
	Wk.7	80
Total (ltrs)		**203**
Cattle 34 %	Wk. 3	116
	Wk. 5	100
Total (ltrs)		**216**

ADAS did not record (volume or nutrient content) of seepage from the beddings or composts; nor did they weight, sample or replace (before composting) the manure scrapped from behind the feed face during housing. In addition, ADAS weighed the soiled beddings before composting, but not after, so the composts' mass loss could not be determined. This may have been resolved using one ton sub-samples kept in litter bags beside the parent composts, turned at the same frequency and weighted, although this would have required pre-emptive knowledge.

Feeding protocol

Dry matter intake was recorded, but no feed refusal data was recorded. In addition, ADAS were unable to provide data on the nutrient content of the silage and concentrates given to the livestock during the trials, nor samples for analysis at Bangor.

3.2.1.2 IGER: Study Design

The former Institute of Grassland and Environmental Research (IGER), at the Aberystwyth Research Centre sought to increase the efficiency of livestock production while minimising its input on natural environments. IGER had a number of research farms, extensive laboratory facilities and scientific expertise, and was in a position to contribute to investigating the effect of different winter feeds (hay and silage) on the performance of woodchip and straw beddings under cattle and sheep, and the subsequent composting of soiled material. This is an important consideration and a priority measurable within the agricultural industry in relation to the bedding's cost efficiency and nutrient (specifically N) input for compost quality. The housing trials were conducted in cattle barns at the main IGER site located at Plas Gogerddan, Aberystwyth, Ceredigion, UK (52°26'01"N, 4°01'02"W). The moisture content of the straw bedding used in both trials was 13.5 % and the mean moisture content of the two woodchip deliveries used in both trials was 50.7 %.

IGER Cattle study

The 8 week IGER cattle housing trial ran from 25th January until 23rd March 2006. Twenty-four 15-month-old heifers were divided equally into four groups (balanced for age, sex, weight and cleanliness), with each group (n = 6) being housed in pens measuring 8.8 m x 4.4 m with a feed barrier along the front. Group 1 was bedded on straw and fed hay, Group 2 was bedded on straw and fed silage, Group 3 was bedded on woodchip and fed hay, and Group 4 was bedded on woodchips and fed silage.

At the start of the housing period pens were bedded to achieve a depth of bedding of 125 mm woodchips or 100 mm straw. To maintain housing and animal cleanliness, additional bedding was applied as and when required. No concentrates were offered to livestock, but forage was offered *ad libitum*, designed to achieve a refusal margin of 10 % (see Table 3.6). Fresh silage was given three times a week and fresh hay was given daily. Table 3.4 details the size, area allowance and livestock number pen^{-1}, as well as the total DM and MC (%) of beddings pen^{-1} during the 8 week housing period, after which all bedding material was chemically and physically characterised.

IGER Sheep study

The 8 week IGER sheep housing trial ran from 25th January until 23rd March 2006. Sixty-four 12-month-old ewe lambs were divided equally into four groups (balanced for age, sex, weight and cleanliness) and housed in a purpose-built experimental sheep shed. Each group (n = 16) was housed in pens measuring 8.8 m x 4.4 m with a feed barrier along the front. Group 1 was bedded on straw and fed hay, Group 2 was bedded on straw and fed silage, Group 3 was bedded on woodchip and fed hay, and Group 4 was bedded on woodchips and fed silage. At the start of the housing period the pens were bedded to achieve a depth of 125 mm woodchips or 50 mm straw. To maintain housing and animal cleanliness, additional bedding material was applied as and when required. No concentrates were offered to the livestock, but forage was offered *ad libitum*, with levels designed to achieve a refusal margin of 10 % (see Table 3.6). Fresh silage was given three times a week and fresh hay was given daily. Table 3.4 provides details on the size, area allowance and livestock number pen^{-1}, as well as the total DM and MC (%) of beddings deployed pen^{-1} throughout the eight week housing period, after which all bedding material was chemically and physically characterised.

Protocol anomalies

Hay and silage feed samples were not analysed and excess bedding was deployed in cattle treatments over the course of the eight week housing trial. This resulted in, firstly, IGER having to order a second woodchip delivery after 5 weeks, which contained a fractionally different moisture content, but similar chemical composition (see Table 3.43); and, secondly, in windrow composts that were too large for the space available. As such, approximately 50 % of the cattle-woodchip and 30 % of cattle-straw composts had to be discarded (see Table 3.19). This action inevitably altered the proportionate composition of the composted material in terms of the precise ratio of bedding and manure inputs during housing.

Tables 3.3 (ADAS) and **3.4 (IGER):** show the number of livestock pen^{-1}; pen area m^2; livestock area allowance m^2 hd^{-1}; dry mass of bedding hd^{-1}, pen^{-1} and % moisture content of raw bedding.

ADAS Housing Treatments	Animals pen^{-1}	Pen area m^2	Density m^2 hd^{-1}	Bedding DM kg hd^{-1}	Bedding DM (kg)	Bedding MC %
Sheep W34	30	30.8	1.03	77.5	2326	34.4
Sheep W53	30	30.8	1.03	74.4	2233	52.7
Sheep W55	30	30.8	1.03	77.9	2336	54.9
Sheep Straw	30	30.8	1.03	19.9	597	10.8
Cattle W34	8	45.6	5.70	355	2840	34.4
Cattle W53	8	45.6	5.70	328	2620	52.7
Cattle W55	8	45.6	5.70	325	2602	54.9
Cattle Straw	8	45.6	5.70	168	1347	10.8

IGER Housing Treatments	Animals pen^{-1}	Pen area m^2	Density m^2 hd^{-1}	Bedding DM kg hd^{-1}	Bedding DM (kg)	Bedding MC %
SSS	16	38.7	2.42	17.2	276	91.9
SSC	16	38.7	2.42	64.9	1038	45.9
SHS	16	38.7	2.42	9.77	156	91.9
SHC	16	38.7	2.42	48.8	781	45.9
CSS	6	38.7	6.45	277	1659	91.9
CSC	6	38.7	6.45	659	3952	45.9
CHS	6	38.7	6.45	268	1609	91.9
CHC	6	38.7	6.45	461	2766	45.9

Tables 3.3 and 3.4 show IGER deployed approximately 100 % more woodchip and 50 % more straw $cattle^{-1}$ than ADAS, but 21 % less woodchip and 50 % less straw $sheep^{-1}$.

Tables 3.5 (ADAS) and 3.6 (IGER): Forage % DM per livestock type and total feed rations (kg) $treatment^{-1}$ and $head^{-1}$ day^{-1}. DMi = dry matter intake.

ADAS Feeding Treatments	Silage % DM	Silage DMi kg pen^{-1}	Silage DMi kg hd^{-1} d^{-1}	Concentrates kg pen^{-1}	Concentrates kg hd^{-1} d^{-1}
Sheep W34	20.4	902	0.54	840	0.5
Sheep W53	20.4	941	0.56	840	0.5
Sheep W55	20.4	941	0.56	840	0.5
Sheep Straw	20.4	946	0.56	840	0.5
Cattle W34	26.7	2285	5.10	896	2.0
Cattle W53	26.7	2016	4.50	896	2.0
Cattle W55	26.7	2150	4.80	896	2.0
Cattle Straw	26.7	2016	4.50	896	2.0

IGER Feeding Treatments	Feed type	Forage % DM	Forage DMi kg pen^{-1}	10 % refusal DM kg pen^{-1}	Forage DMi kg hd^{-1} d^{-1}
SSS	Silage	29.6	824	82.4	0.92
SSC	Silage	29.6	782	78.2	0.87
SHS	Hay	82.7	664	66.4	0.74
SHC	Hay	82.7	662	66.2	0.74
CSS	Silage	29.6	2410	241	7.17
CSC	Silage	29.6	2315	231	6.89
CHS	Hay	82.7	2054	205	6.11
CHC	Hay	82.7	2067	207	6.15

3.2.2 Material characterisation

The initial bedding material (woodchip and straw) was characterised for Total C, Total N, Dissolved Organic Carbon (DOC), Total Soluble Nitrogen (TSN), Dissolved Inorganic Nitrogen (DIN), Dissolved Organic Nitrogen (DON), Ammonium (NH_4^+) and Nitrate (NO_3^-), Salts (Electrical Conductivity, K, Na, Ca), pH and Phosphorus (Total P and Available P), as well as metals (Cu and Zn). The rationale for analysing this selection of nutrients was to assess composting efficiency, as a result of changes in nutrient concentrations during composting and, ultimately, to establish the end product's fertility value. The chemicals analysed for total nutrient content within the composts were selected to determine compost maturity at the end of the composting period, and as indicators of the compost's long term, more stable nutritional value. Over the course of the 7 to 8 month composting, one would expect a large reduction in carbon content as the organic material is broken down and the microbes oxidize C for energy, generating heat and releasing CO_2 (Sweeten and Auvermann, 2008). Organic N in the form of urea, proteins and amino acids quickly become hydrolysed into ammonia-N, which includes both ionized ammonium, (NH_4^+) and un-ionized ammonia, (NH_3). Anhydrous NH_3 is highly soluble, so fundamental processes of decomposition, such as rising temperatures, high pH, moisture evaporation and compost turning also increases NH_3 emissions. Other N loss pathways include denitrification after ammonia-N is nitrified under aerobic conditions into nitrite (NO_2), then rapidly into nitrate NO_3^-, which can be denitrified if anaerobic conditions develop, then emitted as N_2O or N_2. Urea-N, NH_4^+ and NO_3^- can also be lost in seepage if moisture levels are high. However, under the conditions of the present study, volatilization of NH_3 is considered the most prevalent loss mechanism. Electrical conductivity summarizes the concentration of soluble salts, inorganic nitrogen (NH_4^+ and NO_3^-), P, K, Na, Mg, S and Ca, in the compost solution. These nutrients are essential for plant growth, so retention during composting is critical to the finished product's fertility value. Metals Cu and Zn are not highly soluble, so concentrations are only expected to increase relative to compost mass loss; Cu and Zn are essential to plant growth in trace quantities, but toxic at higher concentrations.

3.2.3 Methods of characterisation in raw beddings and composts

3.2.3.1 Determination of pH and Electrical Conductivity (EC)

To determine pH and EC, 20 ml of distilled water was added to 20 cm^3 of compost in a labelled plastic beaker (if the compost absorbed all the water, a further 20 ml was added (i.e. 1:2 compost-to-water v/v)), mixed with a stirring rod and left to stand for 30 minutes. The pH meter was calibrated with pH 4 and 7 standard buffers, and EC meter with a 0.01 M KCl solution, set to 1410 µS cm^{-1}. After the 30 minutes had elapsed, pH and EC was measured. These methods follow those of Smith and Doran (1996) and Rhoades (1982).

3.2.3.2 Determination of Total Carbon and Total Nitrogen

The candidate prepared samples for these analyses then sent them to Prof. Will Cook at Duke University, Colorado for analysis. Samples were oven dried at 80° C for 72 hrs then ground into powder, before (127 mg ±1.26) was added to analyser foil cups. Total C and N was analysed using a dynamic flash combustion system coupled with an infrared (C as CO_2) and chemo-luminescence (N_2O for N) detection system (Nelson and Sommers, 1996). Samples were analysed using an automated LECO CHN2000 Analyzer (Leco Corp., St Joseph, MI, USA). All results are reported on a dry weight basis. The total C (TC): total N (TN) ratio is used in further discussions throughout the thesis.

3.2.3.3 Determination of Dissolved Organic Carbon (DOC) and Total Soluble Nitrogen (TSN)

This method involves the quantitative extraction of DOC and TSN from composts using an equilibrium extraction with distilled water and follows Jones and Willett (2006) and Jones et al. (2002). Samples (30 g wet weight) were shaken (200 rev min^{-1}) with 150 ml distilled water on a flatbed shaker for 1 hour. These were drained (200 µm nylon filter) and centrifuged at 8000 rpm for 10 min. The supernatant solution was analysed for DOC and TSN on a Shimadzu TC-TNV analyzer (Shimadzu Corp., Kyoto, Japan). TSN incorporates the measurement of dissolved organic nitrogen (DON). DOC and TSN are assumed to be the microbially available fractions of total C and N and are referred to as available carbon (AC), available nitrogen (AN) and AC:AN ratio in discussion sections throughout the thesis.

3.2.3.4 Determination of Dissolved Inorganic Nitrogen (NO_3^- and NH_4^+)

Fresh weight samples (30 g wet weight) were mixed with 150 ml distilled water and shaken for 1 hour. Samples were drained (200 µm nylon filter) and centrifuged at 8000 rpm for 10 mins. Supernatant solutions were subsequently colourimetrically analysed for NO_3^- and NH_4^+ on a San$^+$ segmented flow autoanalyser (Skalar UK Ltd, York, UK). During analysis, nitrate is determined by reduction to nitrite via a copperized cadmium column. The nitrite is then determined by diazotizing with sulfanilamide followed by coupling with N-(1-naphthyl) ethlyenediamine dihydrochloride. This method follows that of Mulvaney (1996). All results are reported on a dry weight basis. In the case of NH_4^+, the reaction of NH_4^+ with salicylic acid in the presence of hypochlorite generates a green coloured azo dye complex, which is detected colourimetrically. For both NO_3^- and NH_4^+ the range of standards was 0-10 mg l^{-1} and the limit of detection was 0.05 mg N l^{-1}.

3.2.3.5 Determination of Dissolved and Total Phosphorus

To determine available P, samples (30 g wet weight) were extracted with 150 ml of distilled for 1 hour and filtered (200 µm nylon filter) prior to centrifuging for 10 minutes at 8000 rev min^{-1}. To determine Total P, samples (30 g wet weight) were dried at 80° C for 24 hours and ground. 0.2 g (dry weight) of this was subsequently digested with 1.6 ml concentrated nitric acid, followed by the addition of 0.4 ml concentrated perchloric acid. Digested samples were subsequently filtered (Whatman No. 541 filter paper) and stored for analysis. P in the water and acid extracts essentially followed the method of Murphy and Riley (1962). Briefly, standards (0 to 20 mg l^{-1}) were created and added to all wells of a 96 well reading plate. 180 µl of Ames Reagent (NH_4-molybdate dissolved in H_2SO_4) and 30 µl ascorbic acid (10 % w/v) were then added to the samples and standards. Solution absorbance at 820 nm was subsequently determined with a Versamax® plate reader (Molecular Devices Inc., Sunnyvale, CA). All results are reported on a dry weight basis. The limit of detection was 0.12 mg P l^{-1}.

3.2.3.6 Determination of exchangeable cations

Samples (30 g wet weight) were shaken with distilled water (150 ml), drained and centrifuged for 10 mins at 8000 rev min^{-1}. Concentrations of K, Na and Ca were measured using a Jenway flame emission photometer (Camlab Ltd., Cambridge, UK) and compared against a range of standards, which were prepared from a 1000 mg 1^{-1} stock solution for each element (Rowell, 1994). All results are reported on a dry weight basis.

3.2.3.7 Determination of Cu and Zn

Samples (30 g wet weight) were oven dried overnight and finely ground with a ball mill. 0.2 g was subsequently weighed into a 15 ml test tube and placed into a digestion block after the addition of 1.6 ml nitric acid and 0.4 ml perchloric acid. The tubes were subsequently heated with the following thermal regime: 100° C for 1 hour, 133° C for 1 hour and 150° C for 5 hours, and then left to cool overnight. Solutions were filtered (Whatman No. 541 filter paper) into 20 ml polypropylene vials and analysed on a Varian Techtron AA-975 Atomic Absorption Spectrophotometer (Agilent Technologies Inc., Santa Clara, CA). Appropriate dilutions and standards were utilised. All results are expressed on a dry weight basis.

3.2.4 Composting

Composting at both ADAS and IGER was carried out indoors. ADAS used pyramidal woodchip compost piles approximately 2 m high by 4 m at the base, as shown in Plates 3.1 and 3.2, with smaller, less structurally defined, straw piles.

Plate.3.1: ADAS: Woodchip compost with W53 initial moisture content

Plate 3.2: ADAS: Woodchip compost with W34 initial moisture content

IGER used conventional windrows approx. 4 m long, 2.5 m wide by 2 m high, although compost sizes varied considerably between livestock types. Both sites provided the composts with ample ventilation.

3.2.4.1 Compost temperature

Eltek thermocouple data loggers (Eltek Ltd, Cambridge, UK) were inserted in the centre of each compost treatment at ADAS and recordings taken at 30 minute intervals (Plate 3.3).

Plate 3.3: an electronic data logger inserted into the centre of the 'Shp W53' woodchip compost on the end of a bamboo cane and marked with a yellow tag so it can be easily seen. The white lead relays the temperature readings back to a central portal that is periodically transmitted to a computer in the ADAS Pwllpeiran office.

In the IGER trial, compost temperatures were recorded using data-loggers (Maxim DS1921G 'Thermochron iButtons'), which also recorded temperature at 30 minute intervals (Plate 3.4).

Plate 3.4: Maxim 'Thermochron iButton' Twine was tied through the hole in the fob and a metal tipped cattle prod used to push the device into the centre of the compost heap. When the data needed to be downloaded, the device was retrieved by pulling the twine.

3.2.4.2 Compost moisture content

Samples (~145 g wet weight) were taken at each time point and dried at 80° C for 72 hours. The percentage moisture loss was then calculated as a percentage of fresh weight. This analysis allowed subsequent expression of results on a dry weight basis.

3.2.4.3 Oxygen content

Compost atmospheric oxygen content was measured using a handheld Minolta O_2 analyzer (Konica Minolta Sensing, Inc., Nieuwegein, Netherlands). This was sheathed in a metal pipe with wire gauze fixed over the lead end to allow forced entry into the centre of the compost without the intake pipe becoming blocked with compost debris. The other end of the metal pipe was sealed with insulation tape to stop air from outside the compost being drawn in during sampling. Due to the limited availability of the Minolta O_2 analyzer, ADAS sheep compost O_2 levels were only measured at weeks 10, 12, 16, 22 and 28 and weeks 8, 10, 14, 20 and 26 in the cattle composts.

3.2.4.4 Compost turning

Composts at both sites were turned the day before each sampling event (see Tables 3.7 and 3.8 and Figures 3.1 to 3.4). Turning frequency was designed to balance oxygen requirements, particularly in straw composts, while minimising loss of NH_3, and heat from woodchip piles. ADAS and IGER turned their composts heaps (with a front loader tractor) every two weeks for the first two months, then every four weeks for a further four months and finally at six weekly intervals until the final sample collection (see subsequent section). The soiled bedding was composted over an eight month period to comply with BSI PAS 100 process controls, sampling and testing parameters.

3.2.4.5 Compost quality

Nutrient analyses of the compost material were carried out using the methods described in section 3.2.2.

3.2.4.6 Compost sampling

Following the input of different dietary (IGER only) and livestock feedstock variables during housing, the 8 bedding treatments per trial site were composted (woodchip treatments at ADAS were composted in pyramid heaps and in windrows at IGER). Straw composts at both sites were piled up as efficiently as possible, but nondescript heap forms resulted. Compost samples were collected at the start of the composting trials and then at two weekly intervals; thereafter they were collected for the first two months of composting, then every four weeks for a further two months and finally at six weekly intervals until the final sample collection. This resulted in nine sampling events in total. Four individual 0.5 - 1 kg sub-samples were taken from dispersed points within each treatment in an attempt to overcome sample heterogeneity at each sampling event. While compost treatments were not replicated, four sub-samples were considered justifiable because the composts had been turned the day before. All samples were then analysed by the candidate at Bangor University, except for Total N and C, which were prepared by the candidate then sent to Duke University, Colorado, USA for analysis.

Each sampling event at ADAS and IGER was carried out in a single day ≤ 24hrs after the composts were turned. Tables 3.7 and 3.8, show the compost ages in days and weeks at each sampling event. Within the results section, compost age is referred to in composting weeks.

Table 3.7: ADAS Sheep (left), Cattle (right); pyramid compost age at each turning and sampling event

Sampling Event	Composting Days	Composting Weeks	Sampling Event	Composting Days	Composting Weeks
T0 ~ 20/1/06	15	2	T0 ~ 3/2/06	1	0
T1	29	4	T1	15	2
T2	43	6	T2	29	4
T3	57	8	T3	43	6
T4	85	12	T4	71	10
T5	113	16	T5	99	14
T6	155	22	T6	141	20
T7	197	28	T7	183	26
T8 ~ 17/3/06	232	33	T8 ~ 31/3/06	218	31

Table 3.8: IGER Sheep and Cattle windrow compost age at each turning and sampling event

Sampling Event	Composting Days	Composting Weeks
T0 ~ 25/1/06	9	1
T1	23	3
T2	37	5
T3	51	7
T4	79	11
T5	107	15
T6	149	21
T7	191	27
T8 ~ 23/3/06	226	32

3.2.4.7 Frequency of variable analyses

All listed nutrients were analysed in the raw bedding. Due to cost and/or time pressures, soluble P, TN, TC, (ergo, Total C:N) were only analysed at the start and end of composting. In addition to the cost and time issues, the concentrations of Total P, Cu and Zn were expected to change very little during composting, so were analysed at the end of composting only (see Tables 3.7 and 3.8 for compost ages at each sampling event).

pH and EC were analysed in samples collected at T0, 1, 2, 3, 4, 5, 6, 7 and 8

NO_3^-, NH_4^+, DIN, DON, TSN, DOC, (ergo, AC:N), K, Na, Ca were analysed in samples collected at T0, 2, 4, 6 and 8

Soluble P, TN, TC, (ergo, TC:N) were analysed in samples collected at T0, T8

Total P, Cu and Zn were analysed in samples collected at T8 only

3.2.5 Statistical methods

The Welsh government's funding did not provide for multiple replicates of each housing/bedding treatment at ADAS and IGER, resulting in one bedding-compost treatment^{-1}. While four separate samples were taken from each heap on each sampling occasion, strictly these only provide a more accurate estimate of the composition of each heap and cannot be statistically analysed as independent replicates of each treatment combination. Nonetheless, because the designs of the two experiments were both fully factorial, this still allowed each main treatment effect (defined as bedding type, livestock type and bedding material at ADAS; and bedding, livestock and feed types at IGER) to be tested, by using the full set of interactions between them as the error term in the model. For example; stock on four of the eight bedding-composts at IGER were fed silage (these included two sheep treatments, one bedded on straw and the other on woodchips, and the same under cattle), while the stock in the remaining four pens were fed hay, but in all other aspects, were replicates of the four silage-fed treatments. It is acknowledged this approach does not provide a powerful test of the main effects, but it is a valid conservative model. A cost of the design is that it does not allow any straightforward method of testing the significance of interaction terms. It is reasonable to assume that any complex statistical method to attempt this would only provide weak results and add little useful information. Therefore, in adopting the chosen statistical model it is important to recognise that non-significant results for the main effect treatments do not necessarily imply that they have little impact on the measured variables. Instead, the lack of significance could be the result of large interactions between non-target variables included in each treatment - such as livestock and or bedding type when analysing the influence of feed type - creating a large error term. The selected statistical design is represented using the codes for the individual treatment compost heaps defined above, is to show how each pen/heap acts as a replicate for each main effect treatment (Tables 3.9 to 3.11 for the ADAS experiment and Table 3.12 for the IGER experiment).

A further complication in the implementation of the experiments at ADAS was the different ages of the sheep and cattle composts (by two weeks) at the start of the composting period, resulting from the difference in timing between the two livestock types being turned out of the pens. Because, logistically, the subsequent sampling dates had to be the same for both compost types, this creates a two week disjuncture when the comparisons are made between sets containing cattle and sheep compost heap data. In order to find the solution to this problem likely to introduce the least error, the candidate followed expert advice (personal communications, J. R. Healey) and made visual assessments of the changes in ADAS cattle composts and IGER sheep composts (as a reference only), on a per nutrient basis, to estimate the variability of nutrient changes in the ADAS sheep composts during the first 2 weeks of composting. It was concluded that changes to the ADAS sheep compost's nutrient profile during the initial weeks were likely to have been smaller than those within the cattle composts. Therefore, in order to display the bedding data consistently between the two livestock types to enable comparison, while using the most accurate timeframe, the ADAS experiment results are presented using the cattle compost age. However, when sheep and cattle compost data are presented separately, the correct compost ages are given.

Table 3.9: Summary of composts per bedding type in the ADAS experiment

Independent pens and compost heaps	codes	Bedding type treatments			
		W34	**W53**	**W55**	**Straw**
Sheep Woodchip W34	S34	S34	S53	S55	SS
Sheep Woodchip W53	S53	C34	C53	C55	CS
Sheep Woodchip W55	S55				
Sheep Straw	SS				
Cattle Woodchip W34	C34				
Cattle Woodchip W53	C53				
Cattle Woodchip W55	C55				
Cattle Straw	CS				

Table 3.10: Summary of composts included per bedding material in the ADAS experiment

Independent pens and compost heaps	codes	Bedding materials treatments	
		Woodchip	**Straw**
Sheep Woodchip W34	S34	S34	SS
Sheep Woodchip W53	S53	S53	CS
Sheep Woodchip W55	S55	S55	
Sheep Straw	SS	C34	
Cattle Woodchip W34	C34	C53	
Cattle Woodchip W53	C53	C55	
Cattle Woodchip W55	C55		
Cattle Straw	CS		

Table 3.11: Summary of composts included per livestock type in the ADAS experiment

Independent pens and compost heaps	codes	Livestock type treatments	
		Sheep	**Cattle**
Sheep Woodchip W34	S34	S34	C34
Sheep Woodchip W53	S53	S53	C53
Sheep Woodchip W55	S55	S55	C55
Sheep Straw	SS	SS	CS
Cattle Woodchip W34	C34		
Cattle Woodchip W53	C53		
Cattle Woodchip W55	C55		
Cattle Straw	CS		

Table 3.12: Summary of composts included per treatment type in the IGER experiment

Independent pens and compost heaps	codes	Bedding type treatments		Feed type treatments		Livestock type treatments	
		Straw	**Woodchip**	**Silage**	**Hay**	**Sheep**	**Cattle**
Sheep Silage Straw	SSS	SSS	SSC	SSS	SHS	SSS	CSS
Sheep Silage Chip	SSC	SHS	SHC	SSC	SHC	SSC	CSC
Sheep Hay Straw	SHS	CSS	CSC	CSS	CHS	SHS	CHS
Sheep Hay Chip	SHC	CHS	CHC	CSC	CHC	SHC	CHC
Cattle Silage Straw	CSS						
Cattle Silage Chip	CSC						
Cattle Hay Straw	CHS						
Cattle Hay Chip	CHC						

To mitigate the disparity between the raw bedding and composting week 0 treatment levels, while maintaining continuity within the results section, change in nutrient concentrations during the housing period are presented in Tables 3.23, 3.24 (ADAS) and 3.44 (IGER), as opposed to presenting a contrast of the two data sets together - as is the case for the composting data see section 3.3.4.5 (ADAS) and section 3.3.5.5 (IGER), in which the results for both start and end of composting are determined from data at the same treatment level.

Software programmes used in data analysis and graph generation were MS Excel v2010; SPSS v19.0 (IBM UK Ltd, Portsmouth, UK) and SigmaPlot v10.0 (Systat Software, San Jose, CA).

In order to manage such large data sets, individual analyses were carried out by treatment groups at different stages of the housing – composting continuum. Four separate samples of each raw bedding (4 replicate samples $treatment^{-1}$) used at ADAS and IGER were sent to Bangor University where they were analysed by the candidate. These results of the four samples (raw bedding $type^{-1}$) were considered to be valid replicates, and therefore meaned to provide a single result, a valid representative value for each raw bedding. However, for reasons previously described, the four pseudo-replicates samples collected $compost^{-1}$ sampling $event^{-1}$ was considered statistically invalid. Therefore data analysis was moved up a level and each compost mean (incl. sem) was used as a single data point (incl. sem). For example, analysis of the ADAS W34 bedding type, which was trialled in 1 sheep and 1 cattle pen, is represented as n=2. An alternative method, would have been to determine the mean of all 'pseudo-replicate' samples, i.e. in the case of the ADAS W34 bedding type, n=8 (2 composts * 4 samples $compost^{-1}$). However, time did not allow for all the necessary data set adjustments to be carried out.

ADAS raw bedding treatment groups (number of individual samples) are defined as:

- Bedding types (W34 (n=4); W53 (n=4); W55 (n=4) and straw (n=4))
- Bedding materials (woodchip (n=12) and straw(n=4))

ADAS compost treatment groups (number of compost means) are defined as:

- Bedding types (W34 (n=2); W53 (n=2); W55 (n=2) and straw (n=2))
- Bedding materials (woodchip only (n=6) NB* straw 'type' and 'material' is the same data
- Livestock types (sheep (n=4) and cattle (n=4))

In additional, the unbalanced number of samples per treatment group meant it was not possible to analyse all the ADAS treatment groups in a single multivariate ANOVA using SPSS.

IGER raw bedding treatment groups (number of samples) are defined as:

- Raw bedding types (Wc1 (n=4); Wc2 (n=4) and straw (n=4)) IGER needed two woodchip bedding deliveries.
- Raw bedding materials (woodchip (n=8) and straw (n=4))

IGER compost treatment groups (number of compost means) are defined as:

- Bedding types (straw (n=4) and woodchip (n=4))
- Feed types (silage (n=4) and hay (n=4))
- Livestock types (sheep (n=4) and cattle (n=4))

Nutritional differences BETWEEN the treatments within each group were determined at:

- Raw bedding
- Change during housing
- Start of composting – ADAS week 0* and IGER week 1
- End of composting – ADAS week 31* and IGER week 32

Nutritional changes WITHIN each treatment over composting time:

- ADAS nutrient content at week 0* *versus* week 31*
- IGER nutrient content at week 1 *versus* week 32
- IGER total mass of nutrients at week 1 *versus* week 32

ADAS: Raw bedding

Method of determining nutritional difference between ADAS raw bedding types

Test:	Univariate ANOVA
Post hoc test:	Tukey HSD
Factor:	Degrees of Freedom
Intercept	1
Bedding types	3
Residual	12
Corrected Total	15

Method of determining nutritional difference between ADAS raw bedding materials

Test:	Univariate ANOVA
Post hoc test:	None
Factor:	Degrees of Freedom
Intercept	1
Bedding materials	1
Residual	14
Corrected Total	15

IGER: Raw bedding

Method of determining nutritional difference between IGER raw bedding stocks: straw, woodchip delivery 1 (Wc1) and woodchip delivery 2 (Wc2)

Test:	Univariate ANOVA
Post hoc test:	Tukey HSD
Factor:	Degrees of freedom
Intercept	1
Bedding stocks	2
Residual	9
Corrected Total	11

Method of determining nutritional difference between IGER raw bedding materials

Test:	Univariate ANOVA
Post hoc test:	None
Factor:	Degrees of freedom
Intercept	1
Bedding materials	1
Residual	10
Corrected Total	11

Composting

ADAS: Bedding types

Method of determining nutritional differences between ADAS bedding types at week.0*; week.31* and change during housing

Test:	Multivariate ANOVA
Post hoc test:	Tukey HSD
Factor:	Degrees of freedom
Intercept	1
Bedding types	3
Residual	4
Corrected Total	7

Method of determining nutritional changes during composting in each bedding type at week.0* *versus* week.31*

Test:	Multivariate ANOVA
Post hoc test:	None
Factor:	Degrees of freedom
Intercept	1
Sampling events	1
Residual	2
Corrected Total	3

ADAS: Bedding materials and Livestock types

Method of determining nutritional difference between bedding materials at week.0*; week.31* and change during housing and between livestock types at week.0*; week.31*

Test:	Multivariate ANOVA
Post hoc test:	None
Factor:	Degrees of freedom
Intercept	1
Bedding materials	1
Livestock types	1
Residual	5
Corrected Total	7

Method of determining nutritional difference within ADAS bedding material (woodchip only) at week.0* *versus* week.31*

Test:	Univariate ANOVA
Post hoc test:	None
Factor:	Degrees of freedom
Intercept	1
Sampling events	1
Residual	10
Corrected Total	11

Method of determining nutritional difference in ADAS livestock types at week.0* *versus* week.31*

Test:	Multivariate ANOVA
Post hoc test:	None
Factor:	Degrees of freedom
Intercept	1
Sampling events	1
Residual	6
Corrected Total	7

IGER

Method of determining nutritional differences between IGER bedding types: feed types and livestock types at week.1, week.32 and change during housing

Test:	Multivariate ANOVA
Post hoc test:	None
Factor:	Degrees of freedom
Intercept	1
Bedding	1
Feed	1
Livestock	1
Residual	4
Corrected Total	7

Method of determining nutritional difference within IGER bedding, feed and livestock types at week.1 *versus* week.32 and total mass (TM) of nutrients at week 1 *versus* TM at week.32 (see Appendix IV).

Test:	Multivariate ANOVA
Post hoc test:	None
Factor:	Degrees of freedom
Intercept	1
Sampling events	1
Residual	6
Corrected Total	7

Regression analysis

Changes in nutrient concentration in each treatment type were assessed using linear and, where appropriate, non-linear, decay regression. Linear regression analyses were carried out in both Excel and SPSS, and the resulting correlation co-efficients compared. Once it had been established the p values produced in SPSS were based on the same values and criteria as those in Excel, they were determined as correct. Decay curve regression analyses and associated ANOVA were produced using SigmaPlot. All graphs were generated in SigmaPlot.

3.3 Results

3.3.1 Temperature changes in ADAS and IGER compost treatments

Figures 3.1 to 3.4 show the temporal dynamics of compost temperatures (° C) by livestock type, during each site's 8 month composting trial. The dashed line (- - -) at 65° C indicates UK PAS 100 pathogen guidelines, which require compost temperatures to achieve > 65° C for 7 days (not necessarily consecutively), in order for the compost to be deemed 'sanitized'. This is a compulsory requirement for all commercial producers, and is pertinent to this study if farmers were to choose to re-use the compost as bedding the following year. Temperature is one of the primary indicators of composting performance (Bernal, 2009). With the exception of IGER's silage/woodchip treatments, all woodchip composts achieved thermophilic temperatures (> 50° C) within the first 10 days, but only ADAS's W34 composts met UK PAS100 thermal kill requirements. Most straw treatments reached temperatures > 70° C; the upper limit before microbes are inhibited (Larney et al., 2008(a); Schulze, 1962). Optimal compost temperatures depend largely on feedstock (Nakasaki et al., 1985). Tuomela et al. (2000) report that 40 - 50° C is optimal for lignin degradation, but within the broader spectrum of farmyard manure 40 - 65 °C is considered ideal (Rynk, 1992; Eghball, 2002; Misra, 2003; Kuo, 2004 and Bernal, 2009).

At ADAS, neither W53 nor W55 woodchip treatments under sheep or cattle met the PAS100 requirement (Figures 3.1 and 3.2), indicating a limited capacity to absorb sufficient nutrient-rich liquid excrement to stimulate microbial activity. In contrast, both W34 treatments attained peak temperatures > 70° C and sustained > 65° C for 10 days during the first 3 weeks' composting, as did the sheep-straw. These results show the importance of initial moisture content in determining woodchip's capacity to retain excretal N during housing and achieve the regulatory requirements for re-use.

IGER's woodchip treatments did not achieve 65° C (Figure 3.3 and 3.4), but - critically - neither of the silage-woodchip treatments achieved thermophilic composting. The maximum temperature achieved was 43° C in CSC after 120 days, which was in contrast to the hay fed woodchip treatments, which both reached > 50° C. Again, this result indicated that the *a priori* tested variable at IGER had a controlling influence on composting performance. In summary, the temperature results from both sites suggest that a combination of dry bedding and dry feed stuff would deliver the best composting performance.

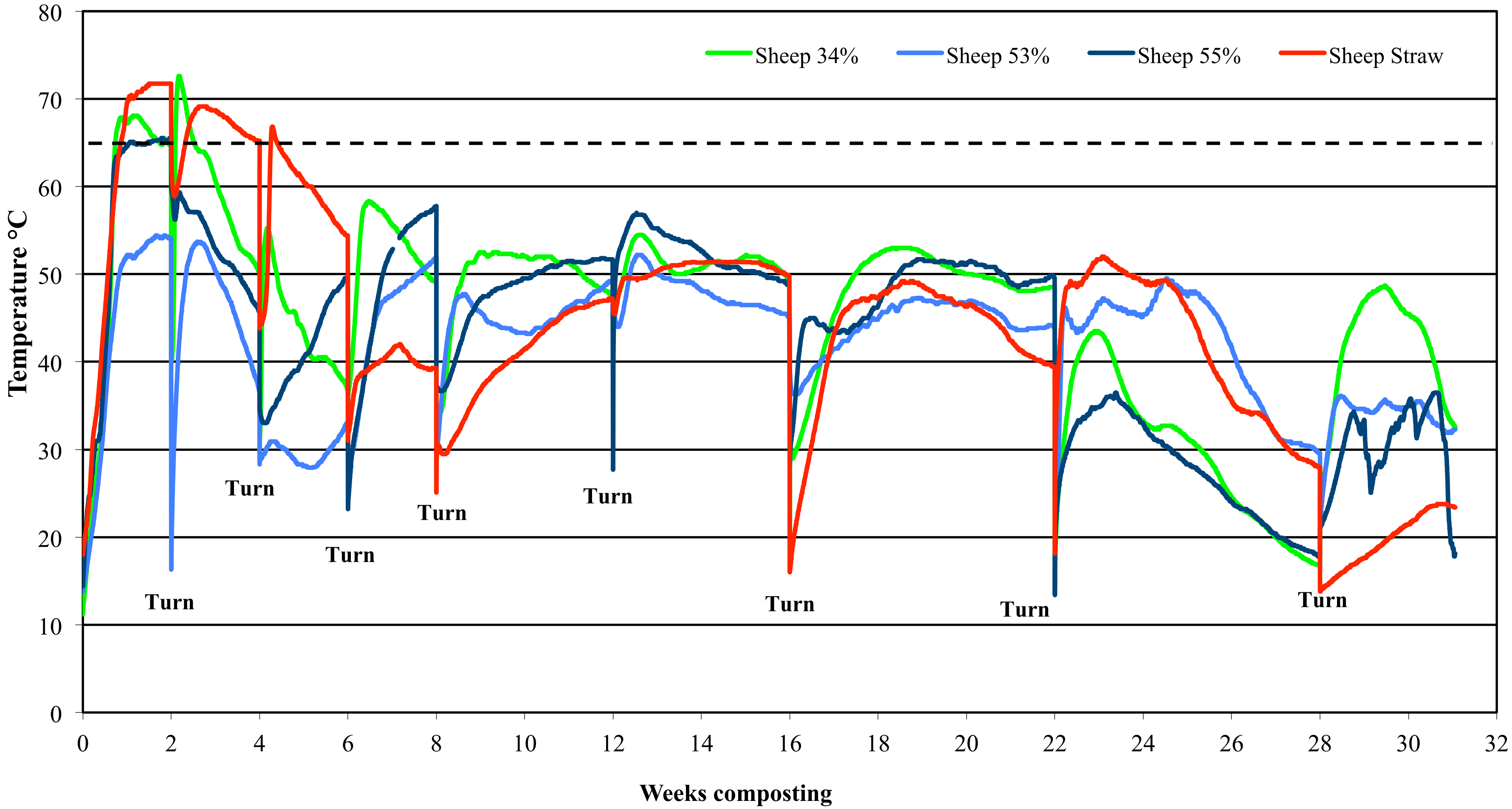


Figure 3.1: *Temperatures (°C) achieved during an 8 month composting period of woodchip and straw derived bedding materials from the sheep trial at ADAS. The graph shows the results for the different initial woodchip moisture contents (34, 53 and 55 %) in comparison to straw. The composts were pyramidal structures and turning events are also shown.*

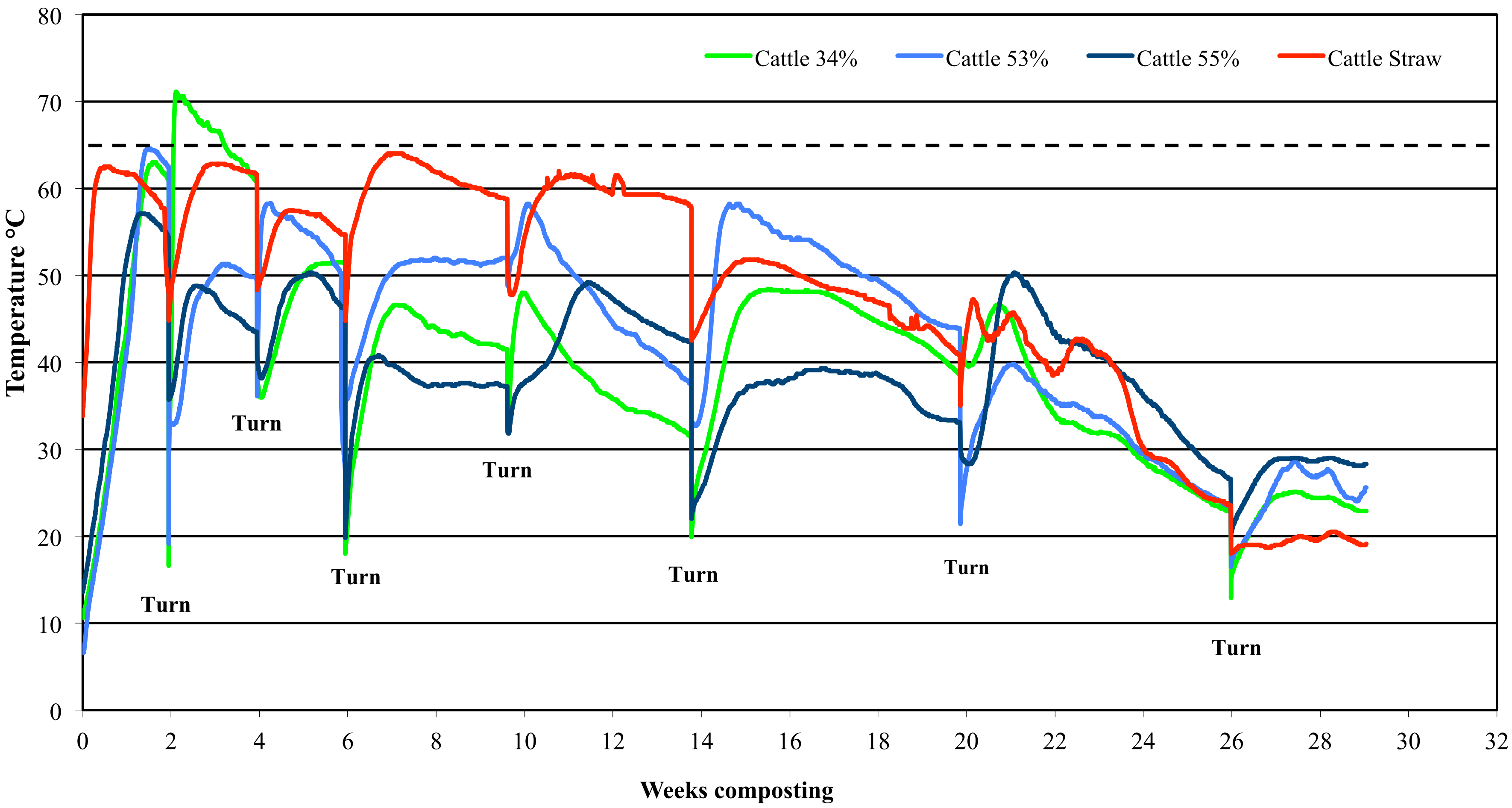


Figure 3.2: *Temperatures (°C) achieved during an 8 month composting period of woodchip and straw derived bedding materials from the cattle trial at ADAS. The graph shows the results for the different initial woodchip moisture contents (34, 53 and 55 %) in comparison to straw. The composts were pyramidal structures and turning events are also shown.*

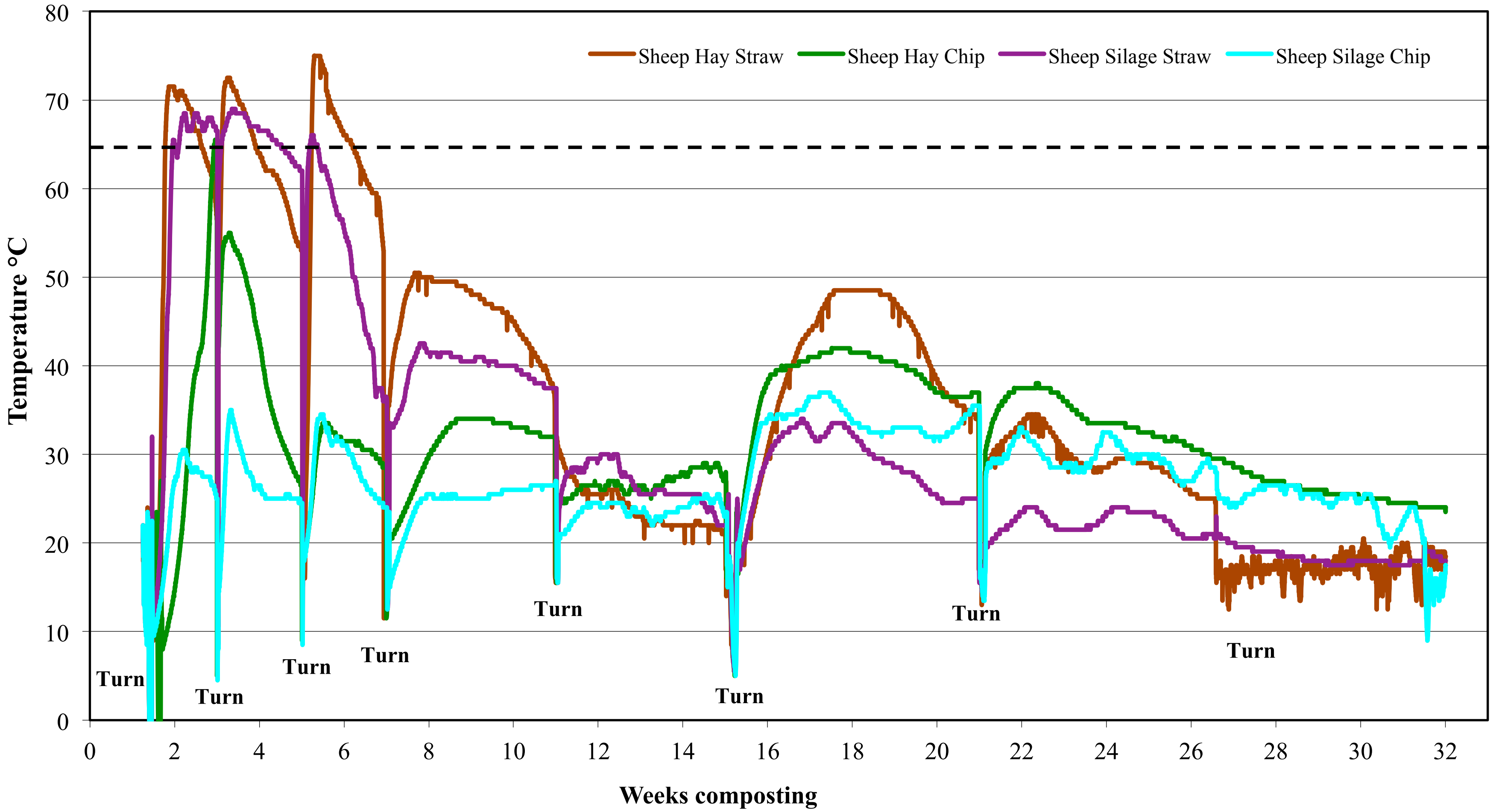


Figure 3.3: *Temperatures (°C) achieved during an 8 month composting period of woodchip and straw derived bedding materials from the sheep trial at IGER. The graph shows the results for the different bedding material-animal feed combinations. The composts were windrow structures and turning events are also shown.*

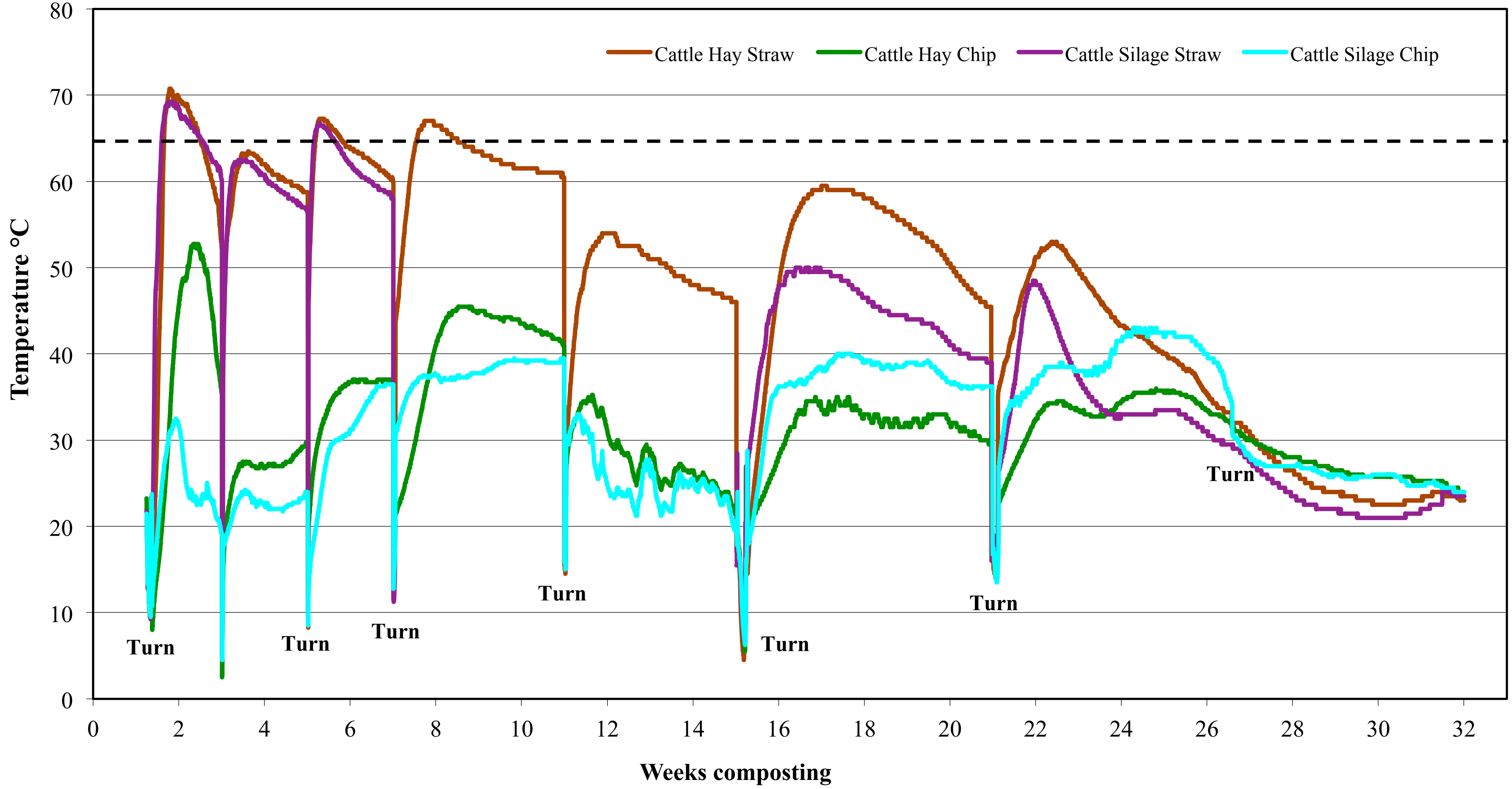


Figure 3.4: *Temperatures (°C) achieved during an 8 month composting period of woodchip and cattle derived bedding materials from the cattle trial at IGER. The graph shows the results for the different bedding material-animal feed combinations. The composts were windrow structures and turning events are also shown.*

3.3.2 Compost moisture contents at ADAS and IGER

3.3.2.1 Woodchip absorbency capacity and water drop penetration time (WDPT)

Two experiments were carried out to determine the water absorbance characteristics of woodchips. The first aimed to establish the water absorbency rate and water holding capacity of woodchips containing different initial moisture contents (50 %, 40 %, 30 %, 20 %, forced air dried (FAd), 6.89 % and 0 %). The second experiment involved measurement of the water penetration drop time (WPDT; Letey, 1969) to characterise the degree of surface hydrophobicity in woodchips with differing moisture contents (50 %, 40 %, 30 %, 20 %, naturally air dried (NAd), 14.5 % and 0 %). (See Appendix I for full details).

Experiment 1: Woodchip absorbency rate and capacity

Woodchips were prepared with initial moisture contents of 50 %, 40 %, 30 %, 20 %, 6.89 % and 0 % (see Appendix I for methods) the treatments were then submerged for 1 hour before being weighed, this was repeated after immersion periods of either 1 day or 1 week. The net weight results are summarised in Figure 3.5 and Table 3.13.

Table 3.13: Woodchip weights recorded at each time interval after immersion in water. Values represent means, incl. ±1 se. % MC represents the initial moisture content of the woodchip.

% MC	Start (g)	se	1 hour (g)	se	1 day (g)	se	1 week (g)	se
50.3 %	82.8	0.62	148	1.97	170	4.15	190	2.94
40.2 %	77.4	0.70	149	0.62	172	1.66	193	2.88
30.2 %	71.7	0.43	145	2.16	165	2.56	188	1.14
20.3 %	66.5	0.13	154	0.87	172	0.54	196	0.70
6.89 %	61.1	0.46	155	2.19	181	2.08	200	1.86
0 %	56.7	0.18	139	2.65	174	1.20	193	1.73

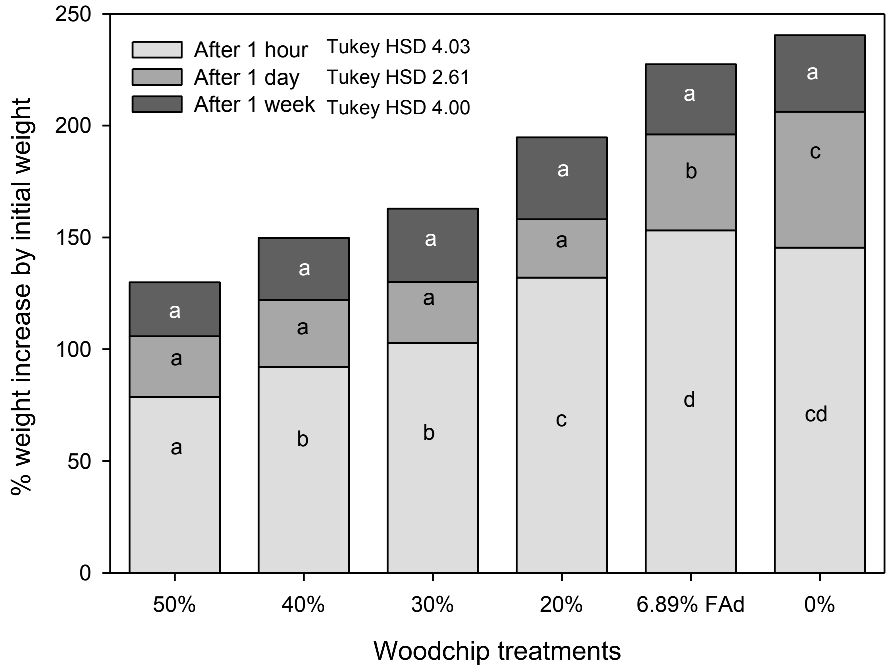


Figure 3.5: *Absorbency rate (speed of absorbency) and capacity (volume of water) of woodchips with different initial moisture contents. Each column increment represents the percentage weight increase within the defined time period, based on the initial mean weight of the treatment. a, b, c and d, in each column increment represent significant (p <0.05) differences between each treatment during that time period.*

Experiment 2: Water Drop Penetration Time (WDPT)

The WDPT test was developed by Letey (1969) and measures the time that hydrophobicity persists on a porous surface. A drop of water is placed on a woodchip surface and the time taken for the liquid to penetrate the matrix is recorded. If the drop does not penetrate immediately, it indicates that the water surface tension is above that of the wood and woodchip surface. This is identified by the water contact angle being greater than or equal to 90°. The WDPT measures the stability of water repellency (Doerr, 1998), which is an important determinant of factors such as soil surface run-off. Letey et al. (2000) recognised that, owing to the radius of some pores being greater than the droplet radius, part of the droplet might disappear, even when the liquid to surface contact angle is more than 90°.

Plate 3.5: 0 % replicate 1, drop 2

Plate 3.6: 50 % replicate 1, drop 3

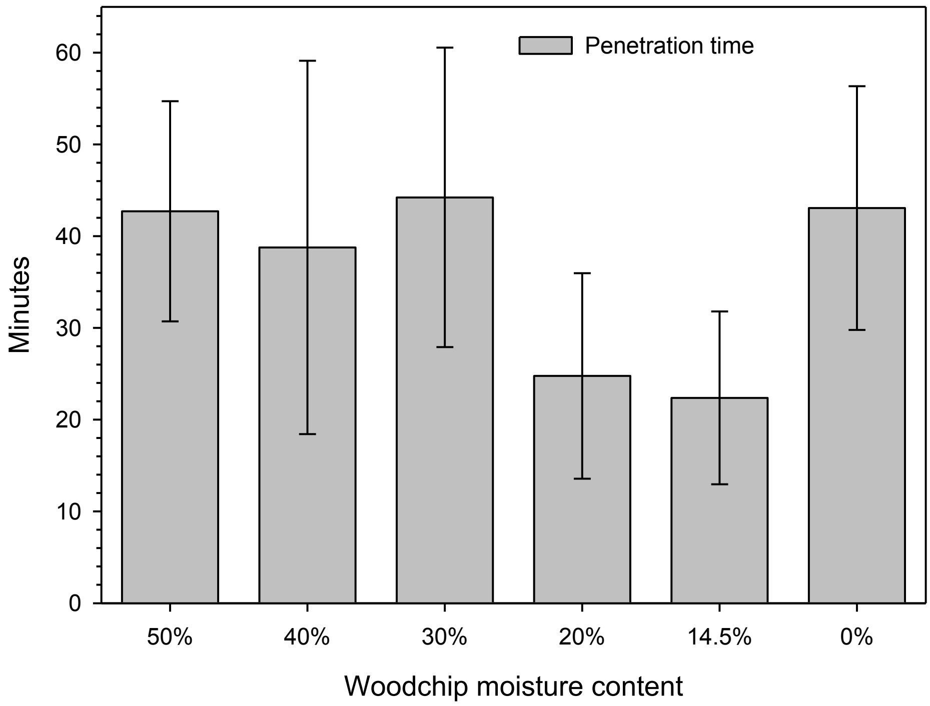
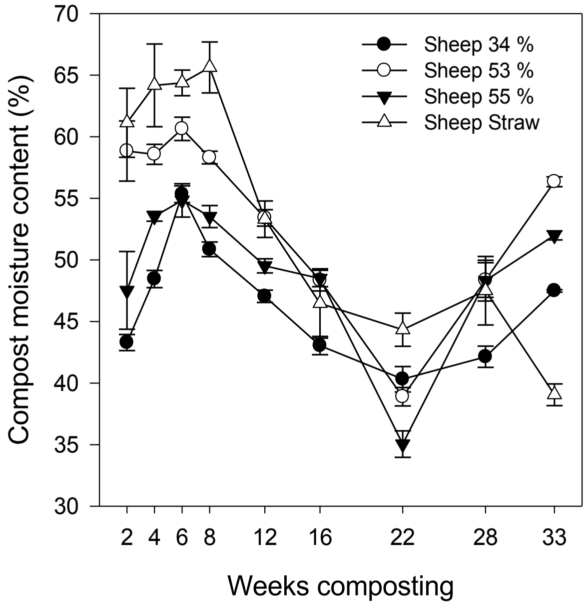
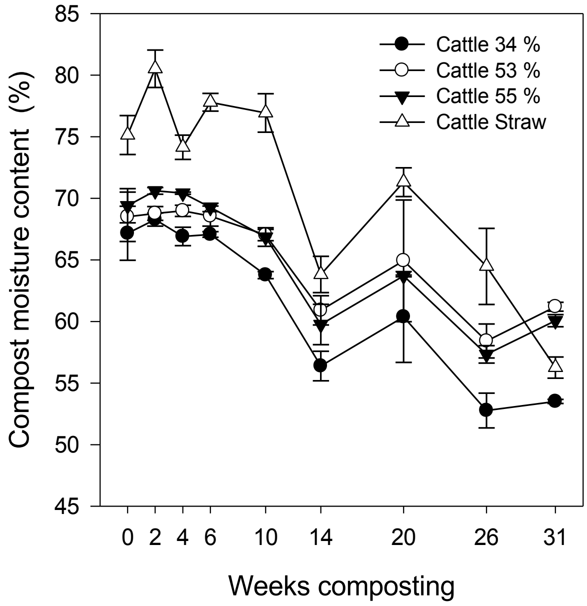


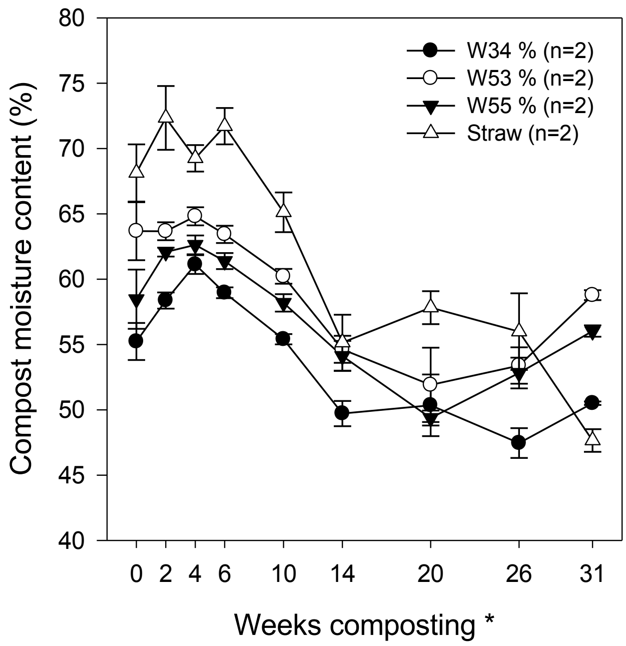
Figure 3.6: *Average water drop penetration time in woodchips of different intrinsic moisture content. Values represent means (n=9) incl. ±1 se.*

The results in Figure 3.6 show that hydrophobicity appears to inhibit absorption in woodchips to a similar extent at all initial moisture contents. However, as < 5 % MC is impractical within a working agricultural scenario, woodchip hydrophobicity may be considered a purely theoretical problem for Welsh farmers.

3.3.2.2 Raw bedding and compost % moisture contents at ADAS







Figures 3.7 (sheep) 3.8 (cattle) *and* ***3.9 (bedding types):*** *show changes in % moisture content sheep (fig. 3.7) and cattle (fig. 3.8) treatment^{-1} during composting at ADAS and the site's 'a priori' variable; bedding type (fig. 3.9). (n=#) indicates the number of composts included treatment^{-1}.Values represent mean ±1 se.*

The sheep composts were 2 weeks old by the first sampling event. As the W34 compost's temperature in the intervening period reached > 70° C (see Figures 3.1 and 3.2), it is reasonable to assume considerable amounts of moisture may have evaporated. It may also be deduced from the data in Figure 3.7 that temperature increases in Sheep 55% during the first 2 weeks of composting reduced the material's moisture content, as the compost MC is 7.5 % lower than the initial 53% in the raw bedding. Conversely, MC in Sheep 53% treatment is still greater after 2 weeks' composting than it was in the raw bedding, suggesting less efficient composting, probably as a result of the woodchips being older, denser material, made from fence post points with a C:N ratio of 592:1 compared to 408:1 and 438:1 in W34 and W55 respectively. Straw bedding clearly absorbed many times its initial MC of 10.8 %, in excretal liquids and sustained high thermophilic temperatures for 3 weeks (Figures 3.1 and 3.2).

The cattle woodchip data suggest ca. 70 % MC is the maximum absorbency capacity of woodchips under indoor livestock housing conditions, as all three woodchip treatment MCs were within a range of 2.2 % on day 1 of composting. Therefore, the W34 treatment absorbed an additional 95 %, compared to only 30 % and 26 % in the W53 and W55 treatments respectively. Although the capacity percentages are different, the pattern of these results reflects those found in the water absorbency experiment described in section 3.3.2.1 and Appendix I. On the strength of this evidence it is reasonable to conclude that drier woodchips have the capacity to absorb greater amounts of excretal liquid, making them more efficient as bedding and facilitating greater microbial activity, hence higher compost temperature.

Table 3.14: Dry matter content in ADAS raw beddings (RB) and additional effluent moisture absorbed during housing in soiled bedding (SB) and 'Manure' (mass of material in SB minus RB). Dry mass (DM), wet weight (WW), moisture content (MC), 'at day #' denotes the age of the treatment compost.

	RB DM kg	RB MC kg	RB WW kg	SB WW kg	SB WW gain kg	SB gain g kg^{-1} of DM	Manure DM kg	Manure WW kg	Manure MC%
Treatment				at day 15	at day 15	at day 15	at day 15	at day 15	at day 15
S34	2326	800	3125	3332	207	88.9	816	2208	63
S53	2233	1177	3409	3546	137	61.4	871	3994	78
S55	2336	1283	3619	3446	-172	-73.8	1747	4334	60
SS	597	65.0	662	962	301	503	841	2738	69
Treatment				at day 1	at day 1	at day 1	at day 1	at day 1	at day 1
C34	2840	977	3818	4748	931	328	519	5482	91
C53	2620	1381	4001	4415	414	158	858	6625	87
C55	2602	1429	4031	4408	377	145	1003	7372	86
CS	1347	145	1492	2359	867	643	560	5311	89

SB (WW) is determined by RB (DM) and compost MC at the time of sampling; SB gain g kg^{-1} of RB (DM) is SB gain (kg) as a percentage of RB DM (kg) *1000. Manure (DM) was determined as compost (DM) – RB (DM) and manure (WW) by compost (WW) – SB (WW).

The ADAS cattle data in Table 3.14 shows that during housing the cattle straw bedding absorbed 643 g of effluent kg^{-1} of raw bedding (DM); twice the weight absorbed by the cattle W34 (328 g kg^{-1}), which in turn, absorbed twice the weight taken up by W53 (158 g kg^{-1}) and W55 (145 g kg^{-1}), reaffirming that woodchip with lower initial moisture content is a more efficient bedding material.

Estimation of N lost in manure removed from ADAS cattle pens

Table 3.15 shows estimates of manure removed from the ADAS cattle treatments during housing and associated loss of N from the composted material. This assessment of N loss is included in the site nitrogen budget presented in section 3.3.6. Manure volume is estimated by age, sex and weight to be 22.5 kg head^{-1} day^{-1} and contain 10 % dry matter (DEFRA (RB209), 2010), resulting in a total manure (DM) input of 1008 kg pen^{-1}. The DM of manure removed is determined as follows: 1,008 kg – (compost DM pen^{-1} – bedding DM pen^{-1}). If the N content of the manure DM is estimated to be 3.6 %, (or 0.36% wet weight) (DEFRA (RB209), 2010) then the total estimated kg N removed pen^{-1} can be calculated (presented in the final column of Table 3.15). However, by DEFRA's estimates; total manure pen^{-1} is 10,080 kg (at 10 % DM) theoretically includes 9,072 ltrs (or kg) of excretal liquid. Therefore, based on the weights of the soiled beddings pen^{-1}; W34 (931 kg), W53 (414 kg), W55 (377 kg) and Straw (867 kg), lost 89.8 %, 95.4 %, 95.8 % and 90.4 % respectively, as seepage during the housing period. However, IGER's cattle fed silage on woodchip seepage volumes (100 ltrs head^{-1}) indicate that much of this liquid may have been absorbed or at least trapped in the bedding layer and then evaporated instead of passing straight through the bedding. This is an unknown and, without empirical data, cannot be satisfactorily determined.

Table 3.15: Estimation of N loss in manure removed from the ADAS cattle treatment pens

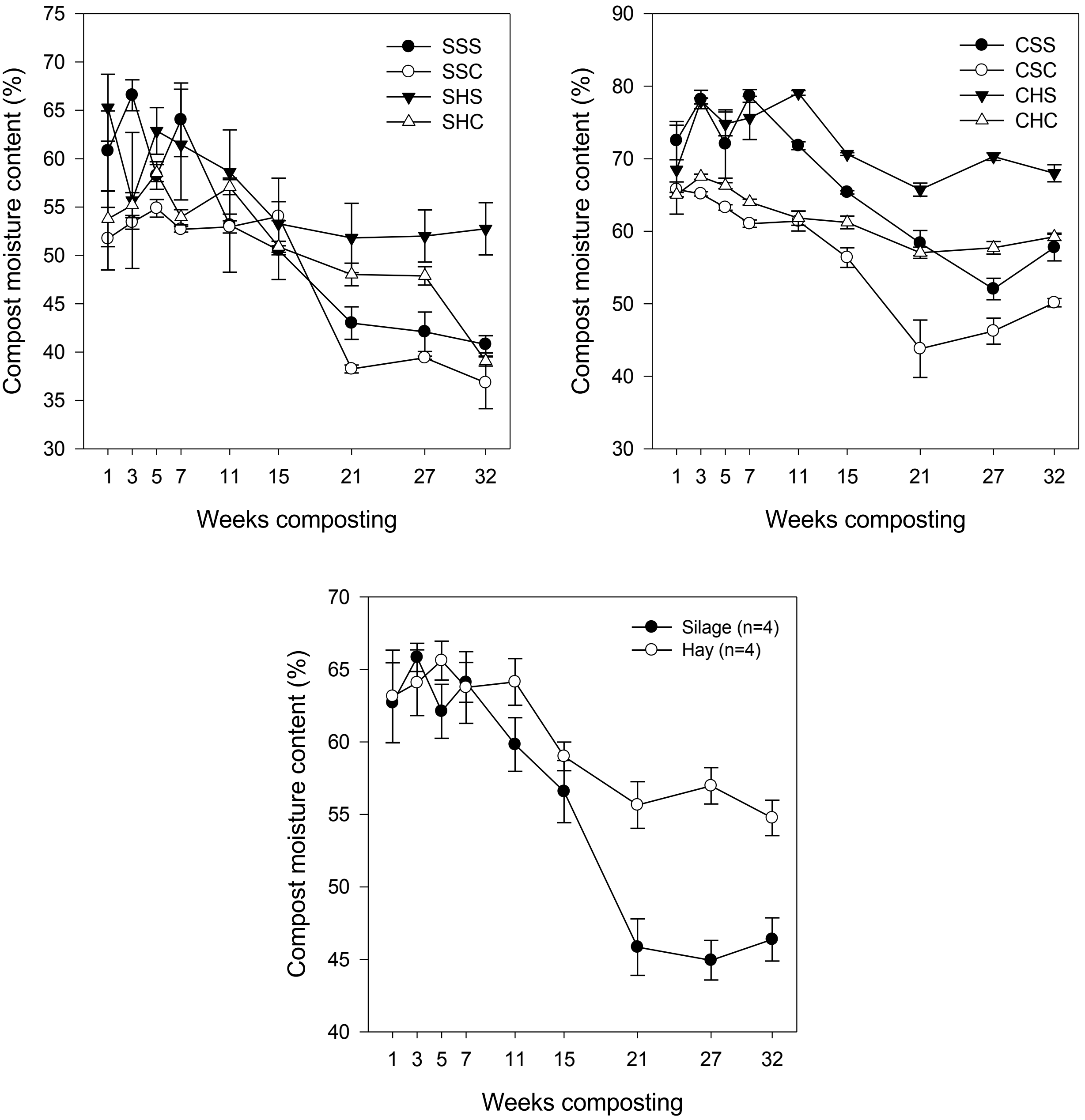
ADAS Treatment	DEFRA estimate of manure DM (kg) pen^{-1}	'Manure' DM (kg) pen^{-1}	Estimated manure removed DM (kg) pen^{-1}	Estimated N removed 3.6 % pen^{-1} DM
C34	*1,008*	519	*489*	*17.5*
C53	*1,008*	858	*151*	*5.36*
C55	*1,008*	1003	*5*	*0.11*
CS	*1,008*	560	*448*	*16.1*

'Manure' refers to additional DM of SB (minus RB DM).
Italics indicate estimates (DEFRA (RB209), 2010).

The figures in Table 3.15 suggest ADAS removed almost 50 % manure (DM) from the cattle W34 and straw treatments; 15 % from the W53 and < 1 % form W55.

3.3.2.3 Raw bedding and compost % moisture contents at IGER

IGER's woodchip compost temperature data suggests the wetter silage diet, limited microbial activity in comparison to hay-fed livestock treatments (see Figures 3.3 and 3.4) although this is not supported by a comparative decrease in hay MC versus silage MC, see Figure 3.12, rather, that compost MC was initially determined by bedding type in sheep Figure 3.10 and cattle Figure 3.11. Although, the temperature increases seen in all four silage-fed composts treatments between weeks 15 - 26 (Figures. 3.3 and 3.4) are clearly illustrated by the decrease in silage MC (Figure 3.12).



***Figures 3.10 (sheep) 3.11 (cattle)** and **3.12 (feed):** show changes in % moisture content sheep (fig. 3.10) and cattle (fig. 3.11) treatment^{-1} during composting at IGER and the site's 'a priori' variable; feed type (fig. 3.12). (n=#) indicates the number of composts included treatment^{-1}.Values represent mean ±1 se.*

In a study of this type, where a woodchip bedding material is directly compared to straw bedding, the different ratios of bedding to manure (B:M) in the bedding-compost after housing are of critical significance. The B:M ratio is probably the most important determining factor in this composting trial, but should it be seen as an inherent physical advantage (or disadvantage) of each bedding type or should the B:M ratio be controlled, in order to test the beddings under the balanced conditions? Table 3.16 shows that in 5 out 6 woodchip composts at ADAS, there is < 400 g of manure to woodchip kg^{-1}, but 1.44 kg sheep manure to straw kg^{-1} and > 400 g of cattle manure to straw kg^{-1}. IGER's sheep B:M ratios are similar to ADAS, (see Tables 3.16 and 3.17) but CHS and CHC have balanced B:M ratios.

3.3.2.4 Compost weights

ADAS

Table 3.16: Total dry matter (DM) of raw bedding (RB) applied to each ADAS treatment and the total DM of composted bedding. DM of manure is determined by deducting the DM of RB from the DM of compost. B:M ratio is the ratio of raw bedding : manure in the compost after housing.

ADAS Treatments	RB DM (kg)	Manure DM (kg)	B:M ratio	Compost DM (kg)	Compost % DM
S34	2326	816	0.35	3142	57
S53	2233	871	0.39	3104	41
S55	2336	1747	0.75	4083	52
SS	589	850	1.44	1438	39
C34	2840	519	0.18	3360	33
C53	2620	858	0.33	3478	32
C55	2602	1003	0.39	3606	31
CS	1347	560	0.42	1907	25

IGER

Due to excess bedding being applied during IGER's housing trials (Table 3.17), parts of the soiled beddings (SB) were discarded in order for the compost windrows to fit back in the space available (see section 3.2.1.2).

Table 3.17: Dry mass (DM) of bedding and manure inputs in all IGER treatments, as well as volumes of seepage and DM of discarded and composted SB from cattle.

IGER Treatments	RB DM (kg)	Manure DM (kg)	B:M ratio	Seepage (ltrs)	SB DM (kg)	Discarded SB DM (kg)	Composted SB DM (kg)	Compost % DM
SSS	276	371	1.34	–	647	–	647	39.2
SSC	1038	422	0.41	–	1460	–	1460	48.3
SHS	156	304	1.94	–	460	–	460	34.7
SHC	781	375	0.48	–	1156	–	1156	46.2
CSS	1659	852	0.51	35	2511	856	1655	27.5
CSC	3952	1339	0.34	600	5291	2958	2333	34.2
CHS	1609	968	0.60	35	2577	670	1907	31.5
CHC	2766	1823	0.66	250	4589	2395	2194	35.0

3.3.3 Compost (%) oxygen contents at ADAS and IGER

3.3.3.1 Oxygen (%) content in ADAS compost treatments

Overall, the woodchip composts maintained high oxygen levels throughout the sampling period (Tables 3.18 and 3.19) primarily as a result of the rigidity of the woodchips, which provided robust structural porosity and maintained airflow throughout the composts. Ideally, all composts should maintain > 10 % oxygen but not < 5 % (Cooperband, 2000), which most of the ADAS composts did, apart from the cattle-straw treatment. This is thought to be due to the straw-based composts' high moisture content and rapid degradation, resulting in structural collapse and compaction, limiting oxygen diffusion within the pile. In addition, the necessity of having a standardized turning schedule for all the composts meant that the turning regime proved too infrequent for wetter straw-manure material. Compost turning is essential to replenish depleted oxygen levels in composts that have high moisture contents and lack a porous structure. However, turning the compost also releases NH_3 trapped within the pile, and, in the case of woodchip based composts, where decomposition rates are slow due a lack of available nutrients, the heat released by the break-up of the material disadvantages mesophilic bacterial colonies, which take time to re-establish temperate conditions. Consequently, the turning schedule over the first two to four months when composting is most active, was too infrequent for straw based composts but too frequent for woodchip composts.

Table 3.18: Oxygen (%) content in ADAS compost treatments between weeks 8 – 26 (cattle) and weeks 10 – 28 (sheep).

Treatment	week 10	week 12	week 16	week 22	week 28
Sheep W34	17.4	18.6	18.6	18.4	19.7
Sheep W53	19.4	20.4	19.5	20.4	20.1
Sheep W55	15.9	19.6	19.8	20.5	20.2
Sheep Straw	15.5	17.3	17.2	17.7	19.8

Treatment	week 8	week 10	week 14	week 20	week 26
Cattle W34	14.5	18.8	18.9	19.8	19.9
Cattle W53	19.5	17.4	20.1	20.1	20.2
Cattle W55	17.7	19.9	18.6	19.9	20.1
Cattle Straw	5.10*	0.90**	3.00**	0.90**	8.80*

* oxygen deficient

** anaerobic

3.3.3.2 Oxygen (%) content in IGER compost treatments

O analysis began on week 9 of the IGER composting period (Table 3.19), by which point IGER's sheep-silage-straw (SSS) compost had cooled to ≤ 40° C. This is in contrast to the sheep-silage-woodchip (SSC) compost which did not achieve 40° C throughout the composting period (see Figure 3.3). It is suggested the anaerobic conditions which developed in both the sheep and cattle silage-fed composts were caused by a lack of heat convection, drawing in fresh air and replenishing depleted oxygen levels. The particularly low temperatures recorded in the sheep-silage-woodchip (SSC) throughout the composting period will certainly have limited convection and resulted in its anaerobicity.

Table 3.19: Oxygen (%) content in IGER compost treatments from week 9 to week 27.

Treatment			week 9	week 11	week 15	week 21	week 27
Sheep	Silage	Straw	5.50*	7.90*	1.60**	1.00**	7.70*
		Woodchip	4.60**	6.70*	15.8	1.20**	6.20*
	Hay	Straw	19.1	20.0	17.9	19.7	19.1
		Woodchip	19.6	20.2	18.9	19.8	19.5
Cattle	Silage	Straw	16.9	18.9	19.7	19.8	19.5
		Woodchip	19.2	19.1	18.7	18.3	19.2
	Hay	Straw	20.2	20.4	20.4	20.4	20.7
		Woodchip	18.2	20.3	20.9	20.4	20.4

* oxygen deficient
** anaerobic

3.3.4 Chemical changes during housing and composting at ADAS

3.3.4.1 Chemical characterisation of raw beddings

Table 3.20: Mean nutrient contents in each of the ADAS raw bedding types and raw bedding materials, incl. ±1 se. Letters a, b, c, d; different letters (by row) after bedding type data denote difference (p <0.05) in variable concentrations. Identical letter(s) denote (p >0.05). Symbols displayed between bedding material data represent (* p<0.05; ** p<0.01 and *** p<0.001) differences in variable concentrations.

ADAS	W34				W53				W55				Straw				Tukey	Wood				Straw		
Variables	(n=4)		se		(n=4)		se		(n=4)		se		(n=4)		se		HSD	(n=12)		se		(n=4)		se
pH	3.42	±	0.03	a	4.23	±	0.02	a	4.04	±	0.03	a	7.70	±	0.54	b	0.38	3.89	±	0.18	***	7.70	±	0.54
EC mS/cm	0.16	±	0.01	a	0.05	±	0.00	a	0.15	±	0.01	a	3.36	±	1.13	b	0.80	0.12	±	0.03	***	3.36	±	1.13
NO_3^- mg/kg	0.23	±	0.19	a	1.10	±	0.43	a	0.92	±	0.54	a	0.00	±	0.00	a	0.51	0.75	±	0.42		0.00	±	0.00
NH_4^+ mg/kg	0.42	±	0.14	a	0.45	±	0.45	a	4.34	±	0.92	a	97.2	±	9.92	b	7.11	1.73	±	1.10	***	97.2	±	9.92
DIN mg/kg	0.65	±	0.29	a	1.55	±	0.65	a	5.26	±	1.41	a	97.2	±	9.92	b	7.16	2.48	±	1.33	***	97.2	±	9.92
DON mg/kg	22.1	±	4.10	a	11.7	±	2.15	a	36.1	±	12.6	a	367	±	136	b	96.9	23.3	±	8.73	***	367	±	136
TSN mg/kg	22.8	±	4.32	a	13.2	±	2.32	a	41.3	±	13.8	a	464	±	136	b	96.8	25.8	±	9.79	***	464	±	136
DOC mg/kg	2462	±	149	a	655	±	47.4	a	2566	±	142	a	6433	±	1783	b	1270	1895	±	471	**	6433	±	1783
AC:N	120	±	22.0	a	53.5	±	9.54	ab	87.1	±	26.2	ab	14.1	±	0.58	b	25.1	86.8	±	23.3	**	14.1	±	0.58
K mg/kg	247	±	5.00	a	125	±	4.15	a	382	±	16.3	a	4947	±	1819	b	1286	252	±	55.6	***	4947	±	1819
Na mg/kg	21.5	±	0.59	a	9.68	±	0.74	a	19.9	±	2.24	a	333	±	103	b	72.8	17.0	±	3.01	***	333	±	103
Ca mg/kg	11.4	±	0.75	b	4.63	±	0.13	a	17.7	±	0.44	c	33.1	±	1.84	d	1.45	11.2	±	2.82	***	33.1	±	1.84
TN g/kg	1.20	±	0.05	a	0.81	±	0.04	a	1.10	±	0.06	a	4.49	±	0.81	b	0.57	1.03	±	0.09	***	4.49	±	0.81
TC g/kg	486	±	3.43	a	479	±	1.16	a	478	±	1.59	a	433	±	3.93	b	3.95	481	±	2.37	***	433	±	3.93
TC:N	408	±	21.6	b	592	±	33.5	c	438	±	20.6	b	100	±	18.8	a	34.4	479	±	46.4	**	100	±	18.8
AP mg/kg	6.55	±	0.31	a	7.61	±	0.52	a	10.1	±	0.37	a	20.2	±	3.24	b	2.36	8.10	±	0.87	***	20.2	±	3.24
TP mg/kg	1481	±	146	a	1024	±	131	a	2279	±	200	a	2715	±	626	a	485	1594	±	298		2715	±	626
Cu mg/kg	2.51	±	0.26	a	9.30	±	5.03	a	7.01	±	3.86	a	4.16	±	0.94	a	4.54	6.28	±	2.53		4.16	±	0.94
Zn mg/kg	13.7	±	0.79	a	83.9	±	3.67	b	15.5	±	1.03	a	6.45	±	0.05	a	2.75	37.7	±	18.0		6.45	±	0.05

Differences in Ca, Zn concentrations and total C:N ratio between the three raw woodchip beddings are considered to be due to W53 being produced from older wood - see section 3.2.1. Initially, the slightly elevated Zn levels found in W53 were thought to suggest that the ex-fence post points had been treated with a wood preservative, as some American brands such as Green's clear wood preservative contain Zinc Naphthenate (23.6 %) and Zinc metal (3 %). However, preservative treated wood usually contains between 1 to 5 g Zn /kg (personal communication with D. L. Jones). Nevertheless, the higher total C:N present in W53 compared to W34 ($p = 0.02$) and W55 ($p = 0.04$), is considered to result from the material being produced from older, core wood. Differences and similarities in nutrient concentrations between wood and straw bedding materials are in line with expectations. Straw contains significantly greater concentrations ($p < 0.01$) of all measured variables, except NO_3^-, total phosphorus (TP) Copper (Cu) and Zinc (Zn).

3.3.4.2 Actual change in nutrient concentrations during ADAS housing trials

Actual change in nutrient concentrations during housing is presented because the raw bedding data and composting week* 0 data originate from different treatment 'levels' - i.e. bedding types, bedding materials and livestock types at the start of composting are all combinations of at least 2 housing treatments, each composed of different percentages of bedding and livestock manure.

Table 3.21: Actual change in nutrient concentrations during the housing period incl. ±1 se and se of diff. (Tukey HSD). Letters a, b, c, d; different letters (by row) after treatment data denote difference ($p < 0.05$) in variable concentrations. Identical letter(s) denote ($p > 0.05$).

ADAS Variable	W34* (n=2)		se		W53* (n=2)		se		W55* (n=2)		se		Straw* (n=2)		se		Tukey HSD
pH	4.88	±	0.16	a	4.05	±	0.26	a	4.05	±	0.07	a	0.47	±	0.36	b	0.33
EC mS/cm	2.41	±	0.26	a	3.01	±	0.30	a	1.86	±	0.84	a	3.09	±	1.93	a	1.51
NO_3^- mg/kg	532	±	252	a	235	±	18.7	a	180	±	163	a	47.8	±	10.2	a	213
NH_4^+ mg/kg	1369	±	839	a	2389	±	136	a	1387	±	1148	a	4242	±	474	a	1064
DIN mg/kg	1901	±	587	a	2623	±	155	a	1567	±	985	a	4290	±	484	a	887
DON mg/kg	424	±	17.1	a	430	±	64.8	a	370	±	154	a	1153	±	361	a	282
TSN mg/kg	2325	±	604	a	3054	±	90.4	ab	1937	±	832	a	5443	±	123	b	735
DOC mg/kg	-112	±	129	a	2239	±	449	a	-514	±	614	a	5654	±	5437	a	3883
AC:N	-107	±	0.22	a	-48.6	±	0.17	c	-61.0	±	0.15	b	-11.8	±	0.88	d	0.66
K mg/kg	3976	±	1232	a	4160	±	667	a	1591	±	710	a	5096	±	148	a	1116
Na mg/kg	955	±	521	a	956	±	333	a	316	±	164	a	1155	±	49.2	a	453
Ca mg/kg	797	±	285	ab	890	±	163	ab	322	±	143	a	1719	±	23.1	b	254
TN g/kg	5.11	±	0.81	a	6.58	±	0.89	a	6.10	±	0.24	a	14.6	±	2.32	b	1.86
TC g/kg	-55.2	±	3.93	a	-40.6	±	4.03	a	-47.9	±	13.2	a	-52.3	±	19.5	a	17.1
TC:N	-337	±	8.55	c	-530	±	6.85	a	-377	±	3.82	b	-76.1	±	1.57	d	8.28
AP mg/kg	253	±	18.5	a	239	±	94.5	a	345	±	52.6	a	354	±	122	a	116

* bedding means include sheep and cattle compost data of different ages; sheep +2 weeks.

pH increases during housing were similar between the woodchip beddings, owing to the buffering effect of manure additions (Table 3.21). In contrast, the straw bedding pH remained much the same throughout the housing period. Increases in the concentration of each nitrogen fraction were similar between all bedding types, but overall total available nitrogen (TSN) increased significantly more in the straw bedding than in both W34 and W55. Decreases in W34 and W55 DOC concentrations are the result of the sheep composts being 2 weeks old when the first samples were taken. For example, DOC concentrations in the S55 treatment had fallen by 1.1 g /kg, from 2566 mg /kg in the raw bedding down to 1437 mg /kg by the time the first samples were analysed. Similarly, concentrations in S34 had fallen by 250 mg/kg. In contrast, DOC in C34 increased by 20 mg /kg and in C55 by 100 mg /kg. These disparities where compounded by the bedding type means not being adjusted proportionately to mass inputs for each livestock type, generating a disproportionate influence from the sheep data. This source of error is acknowledged, but time did not allow for adjustments throughout the datasets and statistical analyses. However, DOC concentrations were very low in the W53 raw bedding, compared to W34 and W55 and the changes during housing resulted in similar DOC contents in all three woodchip types at the start of composting. There is considerably greater DIN (due to NH_4^+ content) in the raw straw than the three woodchip bedding types, but this is not statistically significant (p >0.05) because of the level of variation within the straw stock itself (the result of ADAS using a mixture of wheat and barley straw).

Table 3.22: Actual change in nutrient contents of bedding material and livestock treatments during housing, incl. ±1se. Symbols displayed between treatment data represent significant (* p<0.05; ** p<0.01 and *** p<0.001) differences in variable concentrations between treatments within pairs.

ADAS	Wood*				Straw*			Sheep*				Cattle		
Variable	(n=6)		se		(n=2)		se	(n=4)		se		(n=4)		se
pH	4.33	±	0.19	***	0.47	±	0.36	3.57	±	0.94		3.15	±	1.03
EC mS/cm	2.43	±	0.32		3.09	±	1.93	2.87	±	0.85		2.31	±	0.38
NO_3^- mg/kg	315	±	104		47.8	±	10.2	345	±	159		152	±	66.9
NH_4^+ mg/kg	1715	±	426	**	4242	±	474	1697	±	821	*	2996	±	578
DIN mg/kg	2030	±	358	**	4290	±	484	2042	±	704		3148	±	545
DON mg/kg	408	±	44.9	**	1153	±	361	735	±	261		454	±	122
TSN mg/kg	2439	±	337	**	5443	±	123	2777	±	931		3602	±	659
DOC mg/kg	538	±	578		5654	±	5437	384	±	817		3250	±	2646
AC:N	-72.2	±	11.3	*	-11.8	±	0.88	-57.2	±	19.4		-57.0	±	19.9
K mg/kg	3242	±	662		5096	±	148	3016	±	846		4395	±	704
Na mg/kg	742	±	213		1155	±	49.2	604	±	223		1088	±	216
Ca mg/kg	670	±	145	**	1719	±	23.1	790	±	337		1074	±	251
TN g/kg	5.93	±	0.42	**	14.6	±	2.32	7.15	±	1.76		9.04	±	2.65
TC g/kg	-47.9	±	4.56		-52.3	±	19.5	-59.2	±	5.59	*	-38.9	±	4.20
TC:N	-415	±	37.3	**	-76.1	±	1.57	-327	±	93.5		-333	±	95.1
AP mg/kg	279	±	35.2		354	±	122	226	±	30.4	*	370	±	43.8

* bedding means include sheep and cattle compost data of different ages; sheep +2 weeks.

The low concentration of DIN in the raw woodchip bedding (Table 3.20) is compounded by high losses (assumed to be of volatilized NH_3) during housing, highlighted by the contrasting increases in TSN ($p < 0.01$) between straw and wood-based treatments during housing (Table 3.22). This is a critical farming practice and environmental issue to address if woodchip is to be considered viable as winter livestock bedding. TN increase in straw composts is indicative of straw's performance as a bedding material and the resulting compost B:M ratio (see Table 3.16).

3.3.4.3 Chemical characterisation of treatments at the start of composting

Table 3.23: Mean nutrient contents in each ADAS bedding type at the start of the composting period, incl. ±1 se and SE of Diff. (Tukey HSD). Letters a, b, c, d; different letters (by row) after treatment data denote difference ($p < 0.05$) in variable concentrations. Identical letter(s) denote ($p > 0.05$).

ADAS	W34				W53				W55				Straw				Tukey
Week 0 *	(n=2)		se		(n=2)		se		(n=2)		se		(n=2)		se		HSD
pH	8.29	±	0.16	a	8.28	±	0.26	a	8.09	±	0.07	a	8.17	±	0.36	a	0.33
EC mS/cm	2.57	±	0.26	a	3.06	±	0.30	a	2.01	±	0.84	a	6.45	±	1.93	a	1.51
NO3- mg/kg	532	±	252	a	236	±	18.7	a	181	±	163	a	47.8	±	10.2	a	213
NH4+ mg/kg	1369	±	839	a	2389	±	136	a	1391	±	1148	a	4339	±	474	a	1064
DIN mg/kg	1902	±	587	a	2625	±	155	a	1572	±	985	a	4387	±	484	a	887
DON mg/kg	446	±	17.1	a	442	±	64.8	a	406	±	154	a	1520	±	361	a	281
TSN mg/kg	2347	±	604	a	3067	±	90.4	ab	1979	±	832	a	5907	±	123	b	735
DOC mg/kg	2351	±	129	a	2894	±	449	a	2051	±	614	a	12087	±	5437	a	3883
AC:AN	1.06	±	0.22	a	0.95	±	0.17	a	1.10	±	0.15	a	2.03	±	0.88	a	0.66
K mg/kg	4223	±	1232	a	4285	±	667	a	1973	±	710	a	10043	±	148	b	1116
Na mg/kg	977	±	521	a	966	±	333	a	336	±	164	a	1488	±	49.2	a	453
Ca mg/kg	808	±	285	ab	895	±	163	ab	340	±	143	a	1752	±	23.1	b	254
TN g/kg	6.306	±	0.81	a	7.39	±	0.89	a	7.19	±	0.24	a	19.1	±	2.32	b	1.86
TC g/kg	431	±	3.93	a	438	±	4.03	a	430	±	13.2	a	380	±	19.5	a	17.1
TC:TN	69.67	±	8.55	a	60.2	±	6.85	a	60.0	±	3.82	a	20.3	±	1.57	b	8.28
AP mg/kg	259.7	±	18.5	a	247	±	94.5	a	355	±	52.6	a	375	±	122	a	116

* bedding means include sheep and cattle compost data of different ages; sheep +2 weeks.

Table 3.23 shows TSN levels in straw are significantly ($p < 0.05$) higher than in woodchip bedding-composts. DOC concentrations are approximately four times greater in straw than woodchip bedding, although the difference is not significant ($p > 0.05$) because of high variation between sheep and cattle. Consequently, ratios of AC:N in all four bedding types are < 3:1, but for opposite reasons. Straw composts have an excess of available N, which is prone to loss, whereas woodchip treatments are deficient in both DOC and TSN, likely to result in microbial immobilization (Eghball 2002); it is the actual concentrations of TSN and DOC that are expected to mediate microbial decomposition. The comparatively high EC values and concentrations of NH_4^+ in the W53 treatments are noteworthy and are discussed in section 3.4.

Table 3.24: Mean nutrient contents in ADAS bedding material and livestock treatments at the start of composting, incl. ±1se. Symbols displayed between treatment data represent significant (* p<0.05; ** p<0.01 and *** p<0.001) differences in variable concentrations between treatments within pairs.

ADAS	Wood				Straw			Sheep				Cattle		
Week 0 */ 2	(n=6)		se		(n=2)		se	(n=4)		se		(n=4)		se
pH	8.22	±	0.09		8.17	±	0.36	8.42	±	0.09	*	8.00	±	0.07
EC mS/cm	2.55	±	0.31	*	6.45	±	1.93	3.80	±	1.59		3.24	±	0.43
NO_3^- mg/kg	316	±	104		47.8	±	10.2	346	±	159		153	±	66.9
NH_4^+ mg/kg	1717	±	426	**	4339	±	474	1723	±	841	*	3022	±	602
DIN mg/kg	2033	±	358	**	4387	±	484	2069	±	724		3174	±	569
DON mg/kg	431	±	44.0	**	1520	±	361	844	±	347		563	±	203
TSN mg/kg	2464	±	334	**	5907	±	123	2913	±	1030		3737	±	767
DOC mg/kg	2432	±	253	*	12087	±	5437	3413	±	1148		6279	±	3749
AC:AN	1.04	±	0.09		2.03	±	0.88	1.20	±	0.04		1.37	±	0.51
K mg/kg	3494	±	629	**	10043	±	148	4441	±	1884		5820	±	1577
Na mg/kg	760	±	213		1488	±	49.2	700	±	295		1184	±	232
Ca mg/kg	681	±	143	**	1752	±	23.1	807	±	341		1091	±	255
TN g/kg	6.96	±	0.38	***	19.1	±	2.32	9.05	±	2.60		10.9	±	3.50
TC g/kg	433	±	4.03	**	380	±	19.5	410	±	16.6	*	430	±	10.2
TC:TN	63.3	±	3.61	**	20.3	±	1.57	55.8	±	12.2		49.2	±	10.4
AP mg/kg	287	±	35.6		375	±	122	237	±	31.2	*	381	±	46.7

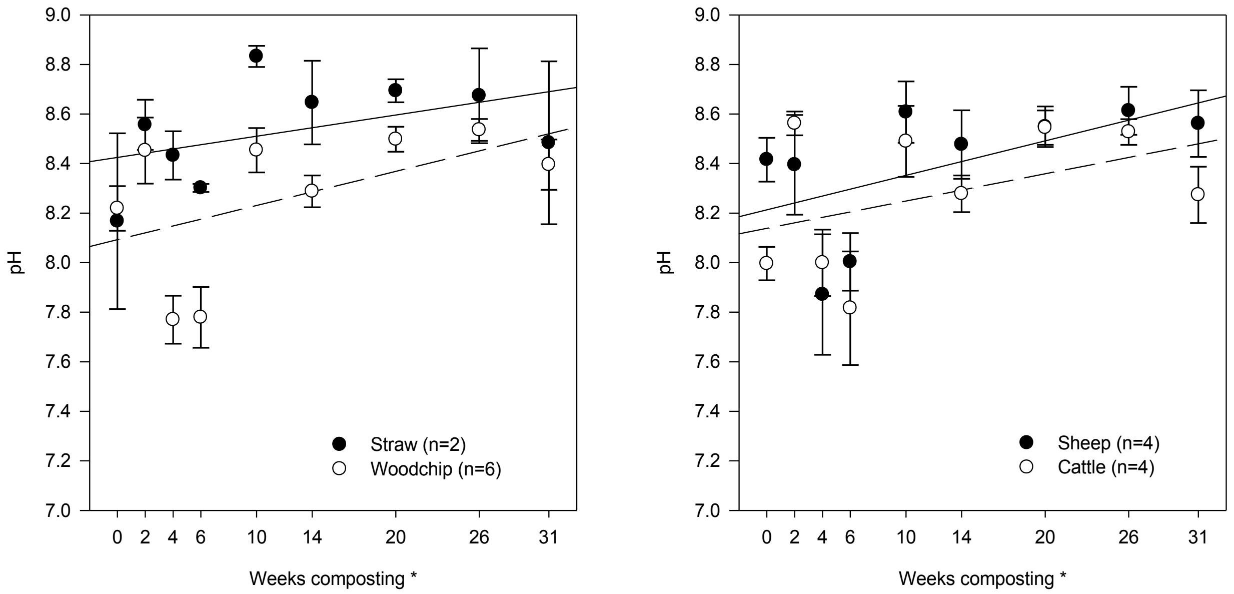
* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks.

Table 3.24 shows differences in nutrient concentrations between bedding materials (wood and straw) and highlights the capacity of straw bedding to retain greater volumes of manure (liquid and faeces) than woodchip. Cattle composts contain greater amounts of manure, hence higher concentrations of ammonium and soluble P. The fractionally lower pH in cattle than sheep treatments may result from anaerobicity developing within the manure fraction. Said-Pullicino et al. (2007) state that drops in pH are usually associated with anaerobicity, but only the straw treatments showed periodical anaerobicity (see Tables 3.18 and 3.19) although small anaerobic pockets at the centre of the woodchip piles cannot be ruled out. In addition, as shown by the nutrient budgets (section 3.3.6) there were high levels of N loss during housing. The significantly lower EC readings in woodchip compared to straw treatments (p <0.05) is attributable to the differences in K, Ca and NH_4^+. Straw composts contain higher concentrations of most measured nutrients than woodchip (see Table 3.24).

3.3.4.4 Chemical changes during composting - Regression analysis

Regression analysis of pH, EC, NO_3^-, NH_4^+, DIN, DON. TSN, DOC, AC:AN, K_2O, Na, and Ca within ADAS bedding and livestock types; for individual bedding treatment results see Appendix VII. Most nutrient profiles were analysed using linear regression, however, concentrations of NH_4^+ decreased rapidly then remained low, so an exponential decay curve was used. Similarly, DIN in ADAS straw and cattle treatments decreased rapidly, but then increased at week 31, befitting an exponential decay / linear combination curve. Treatment (n= #), shown on each graph, refers to the number of compost heap means (not individual samples) included in each treatment data.

pH



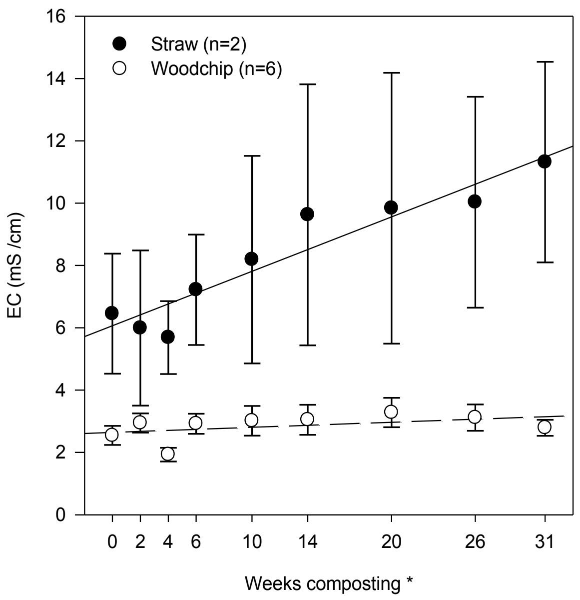
Figures 3.13 (bedding) *and* ***3.14 (livestock):*** *show the relationship between pH and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Values represent mean ±1 se. Fig. 3.13 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.14 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

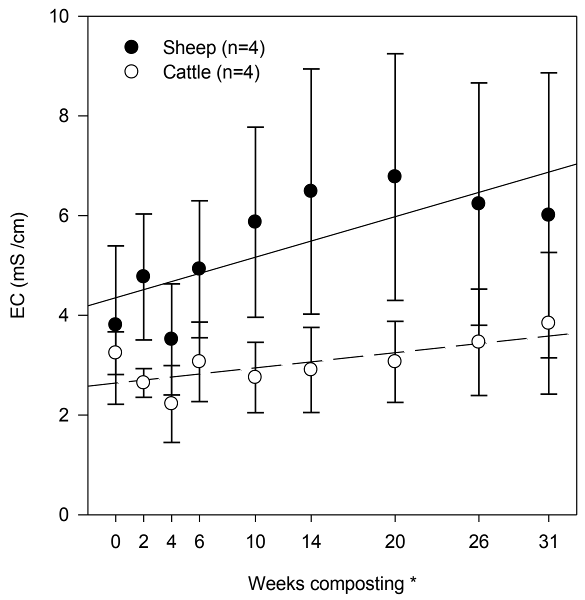
Table 3.25: pH regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in pH within treatments.

Treatment	Equation	R^2	p. value
Straw	y = 0.0086x + 8.4245	R² = 0.2038	.223
Woodchip	y = 0.0138x + 8.0928	R² = 0.2628	.158
Sheep	y = 0.0139x + 8.2132	R² = 0.3251	.109
Cattle	y = 0.011x + 8.1382	R² = 0.1867	.245

Figures 3.13 and 3.14 show pH fluctuations are greatest during composting weeks 0 – 14, when microbial activity is expected to be highest. In all treatments pH is > 7.5 throughout composting with a slight upward trend, indicating substantial NH_3 loss, particularly straw at week 10; pH > 8.8. Table 3.25 shows that the rate of change is not consistent over time.

Electrical Conductivity (EC)





***Figures 3.15 (bedding)** and **3.16 (livestock):** show the relationship between EC and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Values represent mean ±1 se. Fig. 3.15 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.16 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

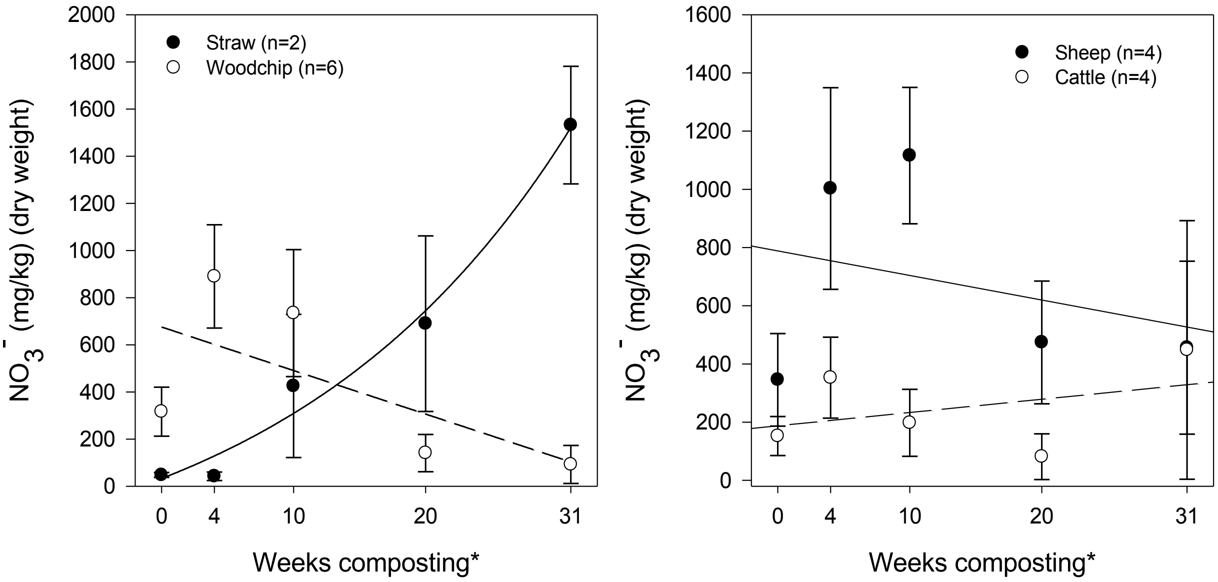
Table 3.26: EC regression equations and corresponding R^2 values per treatment; (p<0.05) shows that composting time is a significant factor in determining changes in EC within treatments.

Treatment	Equation	R^2	p. value
Straw	y = -0.0353x + 7.9872	R^2 = 0.0130	**< .001**
Woodchip	y = -0.0458x + 3.1364	R^2 = 0.2378	.226
Sheep	y = 0.0813x + 4.3546	R^2 = 0.5802	**< .05**
Cattle	y = 0.0305x + 2.6386	R^2 = 0.5065	**< .05**

Table 3.26 and the corresponding Figures 3.15 and 3.16 show that EC (relating to soluble salt concentrations) increases linearly over time in all treatments except woodchip. Furthermore, the rate of increase is clearly greater in straw than in woodchip; this illustrates woodchip bedding's

deficiency in a broad spectrum of soluble nutrients, and its consequently low rate of decomposition. In addition, the rate of increase is clearly greater in sheep than cattle compost.

Nitrate (NO_3^-)



***Figures 3.17 (bedding)** and **3.18 (livestock):** show the relationship between NO_3^- and composting time in bedding and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed lines, to Woodchip and Cattle treatments. NO_3^- in straw is analysed using an exponential growth curve (3 parameters) f = y0+a*exp(b*x). Values represent mean ±1 se. Fig. 3.17 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.18 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

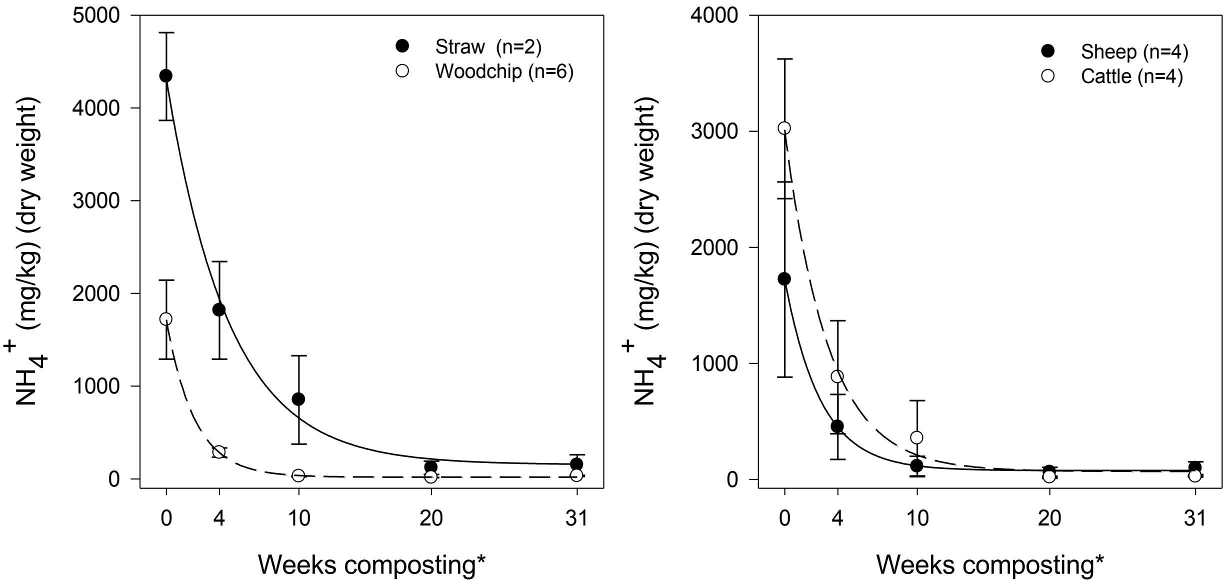
Table 3.27: NO_3^- regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in NO_3^- within treatments.

Treatment	Equation	R^2	p. value
Straw	y = 32.85 * exp0.046x	$R^2 = 0.9677$	**< .05**
Woodchip	y = -18.47x + 674.77	$R^2 = 0.2256$	.238
Sheep	y = -8.4409x + 788.65	$R^2 = 0.0904$	.623
Cattle	y = 4.5625x + 187.38	$R^2 = 0.1455$	.526

Typically, NO_3^- concentrations increase over composting time, (see ADAS straw data in Figure 3.17) and are, therefore, more accurately analysed using an exponential growth curve. However, changes in NO_3^- within the woodchip treatment - and by inclusion, in the sheep and cattle treatment data - meant NO_3^- profiles in all three treatments were analysed using linear regression. The straw compost data shows high levels of nitrification throughout composting (Table 3.27), but only up to week 4 in the woodchip treatments (note: NO_3^- levels in the woodchip at week 0 show more influence from the 2 week old sheep fractions than the straw composts at this point). After week 4, nitrate levels in woodchip-based composts decrease, reaching near zero by week 31. The reason for this reversal is clear when compared to NH_4^+ levels over the same period. Figures 3.19 and 3.20, show NH_4^+ concentrations quickly decreased from week 0 to week 4, due to nitrification, immobilization or loss, as gas or liquid. Figures 3.17 to 3.20 show that decreasing NH_4^+ levels cross with increasing concentrations of NO_3^- ca. week 4. After which, it is suggested microbes are forced to convert NO_3^- back into NH_4^+ for growth and function; an energy inefficient process, and as both DOC and TSN are already low (see Figures 3.25 to 3.28), microbial activity is reduced and decomposition slows.

The ratios of manure, woodchip and straw within the collective of composts that make up each livestock treatment are considered to be the reason why the process is delayed in the sheep treatment, which achieved higher levels of nitrification than cattle, as microbes did not need to assimilate nitrate until after week 12.

Ammonium (NH_4^+)



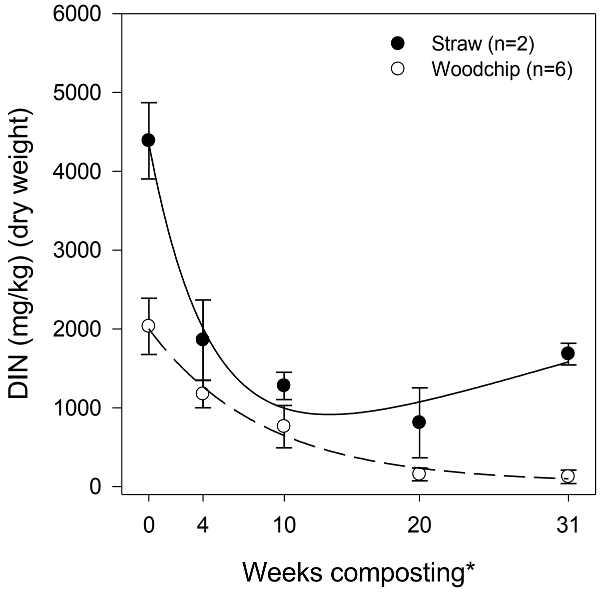
Figures 3.19 (bedding) *and* ***3.20 (livestock):*** *show the relationship between NH_4^+ and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. All treatments analysed using an exponential decay curve (3 parameters) $f = y0+a*exp(-b*x)$. Values represent mean ±1 se. Fig. 3.19 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.20 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

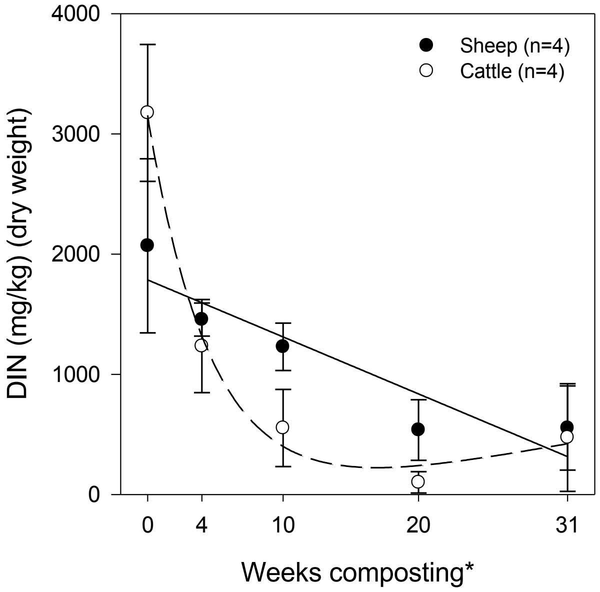
Table 3.28: NH_4^+ regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in NH_4^+ within all treatments.

Treatment	Equation	R^2	p. value
Straw	$y = 4309.2 * \mathrm{exp}{-0.21x}$	$R^2 = 0.9898$	**< .01**
Woodchip	$y = 1716.8 * \mathrm{exp}{-0.47x}$	$R^2 = 0.9998$	**< .001**
Sheep	$y = 1723.3 * \mathrm{exp}{-0.37x}$	$R^2 = 0.9993$	**< .001**
Cattle	$y = 3011.6 * \mathrm{exp}{-0.31x}$	$R^2 = 0.9906$	**< .01**

Figures 3.19 and 3.20 show decreases in NH_4^+ concentrations decreased rapidly during the first weeks of composting and Table 3.28 shows the rate of decrease in all treatments over time, was significantly ($p<0.01$) correlated to the predictions of the respective decay curve regression models.

Dissolved Inorganic Nitrogen (DIN)





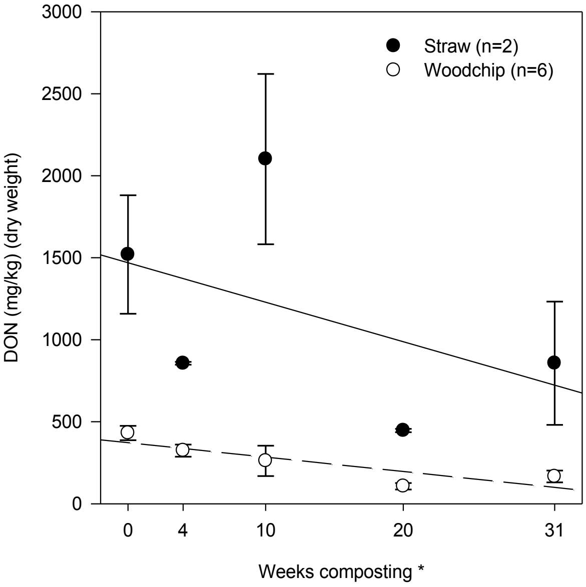
***Figures 3.21 (bedding)** and **3.22 (livestock):** show the relationship between DIN and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Straw (Fig 3.15) and Cattle (Fig 3.16) treatments are analysed using an exponential decay / linear combination curve f = y0+a*exp(-b*x)+c*x. Woodchip (Fig 3.15) is analysed using an exponential decay curve (3 parameters) f = y0+a*exp(-b*x). Values represent mean ±1 se. Fig. 3.21 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.22 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

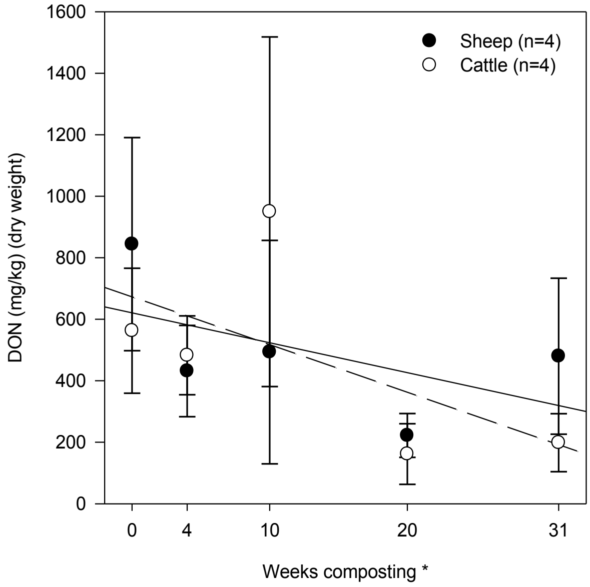
Table 3.29: DIN regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in DIN within treatments.

Treatment	**Equation**	R^2	**p. value**
Straw	y = 4352. 5 * exp-0.21x + 50.5x	$R^2 = 0.9053$	. 195
Woodchip	y = 2004.4 * exp-0.12x	$R^2 = 0.9769$	**< .05**
Sheep	y = -47.411x + 1784.8	$R^2 = 0.8486$	**< .05**
Cattle	y = 3153. 5 * exp-0.21x + 20.8x	$R^2 = 0.9642$	.120

Figures 3.21 and 3.22 show DIN decreased in all treatments; straw treatments contained higher concentrations than woodchip throughout composting; and DIN in ‘cattle’ appeared to decrease more rapidly than ‘sheep’ (+ 2 wks.). Table 3.29 shows rate of decreased in woodchip and sheep treatments over time, was significantly ($p<0.05$) correlated to values predicted in the respective decay curve regression models (note: ‘sheep’ (p= <0.05) but with the lowest R^2 value, illustrating the linear model’s greater tolerance for variability than the ‘fitted’ decay curve regression model).

Dissolved Organic Nitrogen (DON)





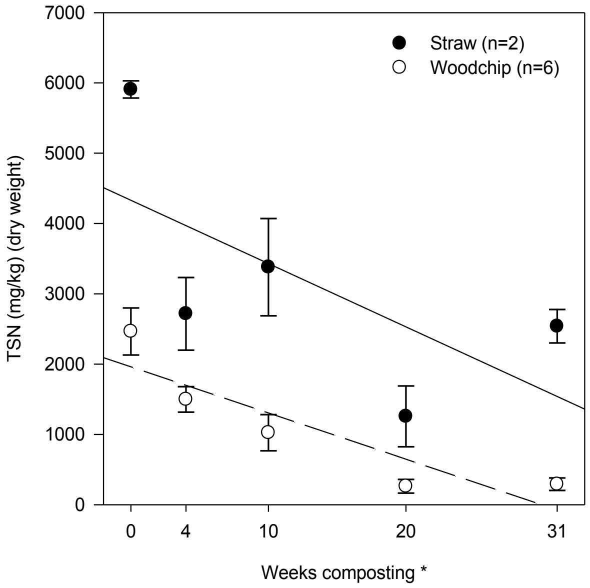
***Figures 3.23 (bedding)** and **3.24 (livestock):** show the relationship between DON and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Values represent mean ±1 se. Fig. 3.23 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.24 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

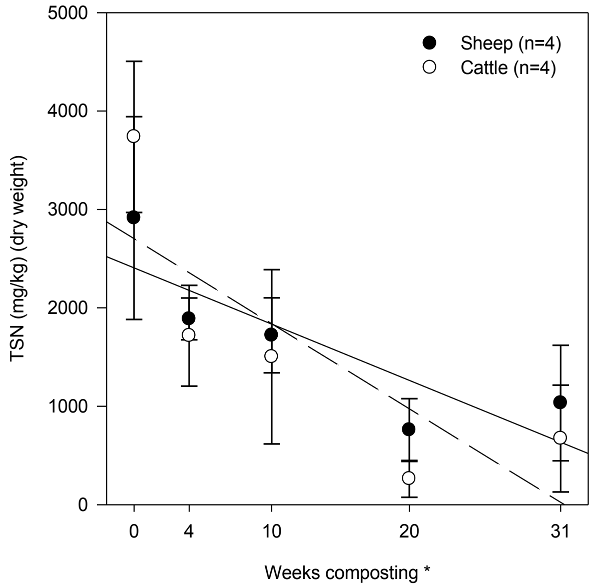
Table 3.30: DON regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in DON within treatments.

Treatment	Equation	R^2	p. value
Straw	y = -24.082x + 1469.3	$R^2 = 0.2145$	.432
Woodchip	y = -8.8019x + 372.51	$R^2 = 0.7459$	.059
Sheep	y = -9.7255x + 620.6	$R^2 = 0.2980$	.341
Cattle	y = -15.518x + 672.79	$R^2 = 0.3733$	.274

Figures 3.23 and 3.24 show straw treatments contained higher DON concentrations than woodchip throughout composting and error bars show levels of DON were consistently low in all the woodchip composts. DON concentrations decreased at a similar rate over time in the two livestock treatments; however the variation within each was large so the linear change over time was not significant in either (Table 3.30).

Total Soluble Nitrogen (TSN)





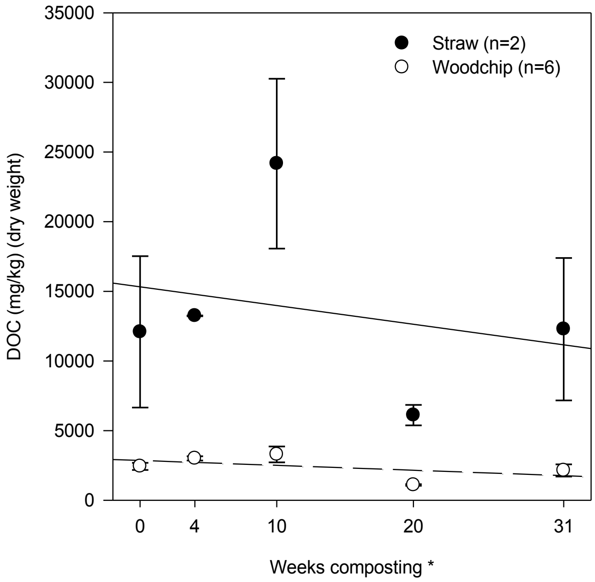
***Figures 3.25 (bedding)** and **3.26 (livestock):** show the relationship between TSN and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Values represent mean ±1 se. Fig. 3.25 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.26 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

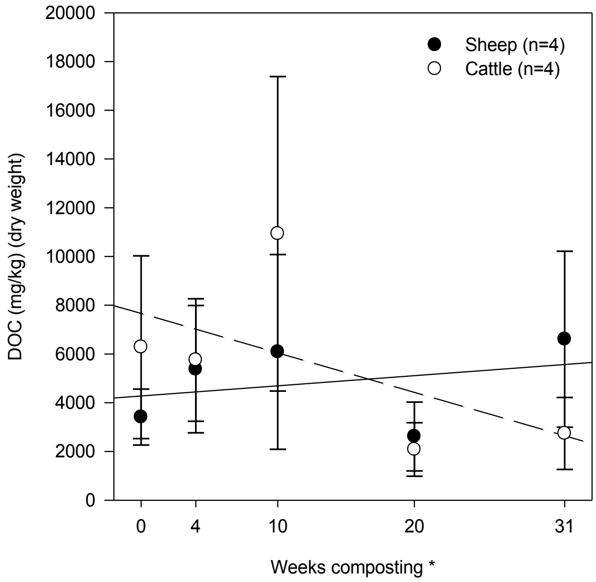
Table 3.31: TSN regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in TSN within treatments.

Treatment	**Equation**	**R^2**	**p. value**
Straw	y = -89.998x + 4329.1	$R^2 = 0.4338$	.227
Woodchip	y = -65.685x + 1961.6	$R^2 = 0.8064$	**< .05**
Sheep	y = -57.136x + 2405.4	$R^2 = 0.7290$	.066
Cattle	y = -86.389x + 2701.6	$R^2 = 0.6518$	.099

TSN decreased over time in all treatments; the linear decrease was significant in woodchip, which had lower TSN than straw throughout. The small woodchip treatment error bars (see figure 3.25) show that the variation in initial moisture content between the raw bedding and livestock types had very little influence on determining TSN concentrations over time (Table 3.31).

Dissolved Organic Carbon (DOC)





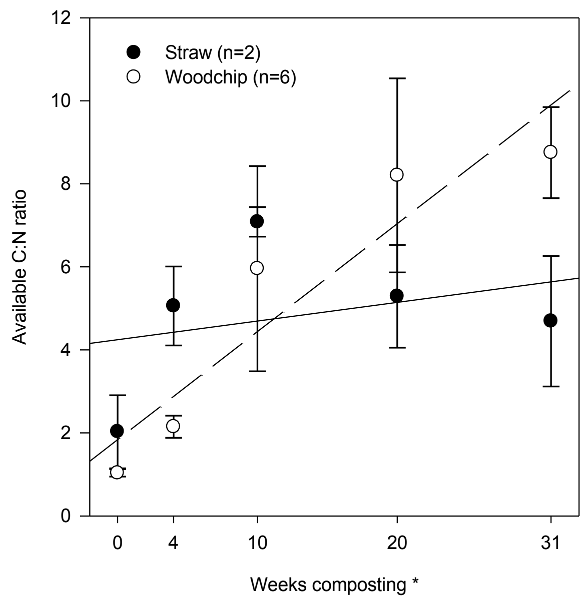
***Figures 3.27 (bedding)** and **3.28 (livestock):** show the relationship between DOC and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Values represent mean ±1 se. Fig. 3.27 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.28 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

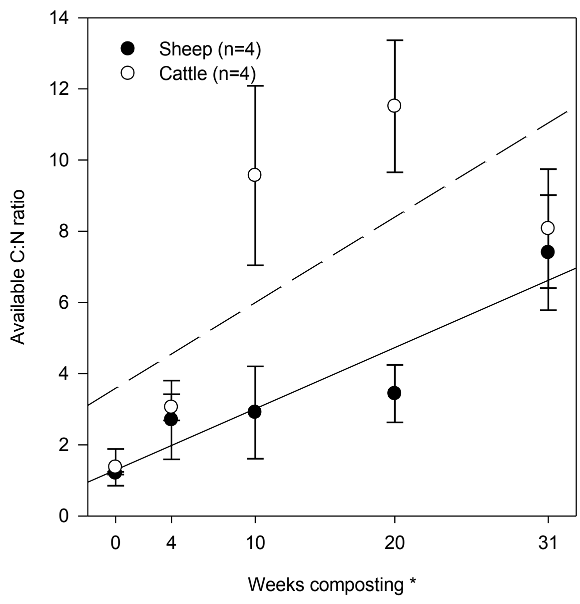
Table 3.32: DOC regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in DOC within treatments.

Treatment	Equation	R^2	p. value
Straw	y = -134.43x + 15325	$R^2 = 0.0664$	.676
Woodchip	y = -35.391x + 2852.5	$R^2 = 0.2710$	.368
Sheep	y = 41.495x + 4280.2	$R^2 = 0.0911$	.622
Cattle	y = -161.8x + 7661.2	$R^2 = 0.3347$	.307

Figures 3.27 and 3.28 show bedding type was the determining factor controlling DOC concentrations over time, and contrast between beddings emphasizes DOC concentrations were much lower in woodchip than straw composts throughout. The difference in (non-significant) trends between livestock treatments in Table 3.32 may be indicative of microbial responses to the higher ratios of manure to bedding in the collective of sheep composts compared to cattle.

Available C:N ratio (AC:N)





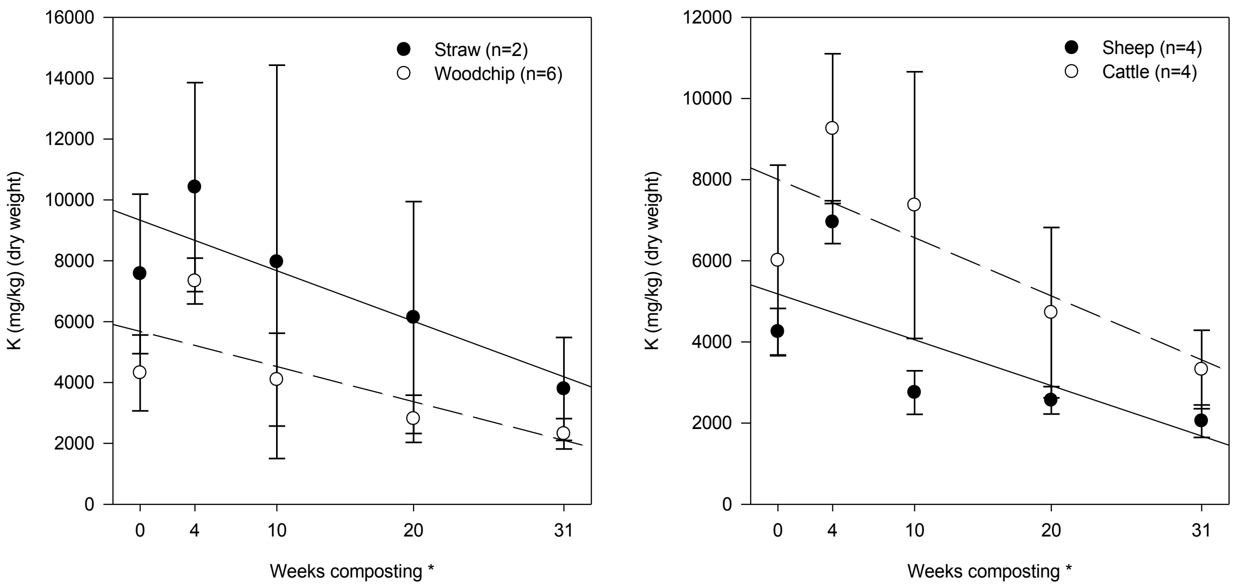
Figures 3.29 (bedding) *and* ***3.30 (livestock):*** *show the relationship between AC:N and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Values represent mean ±1 se. Fig. 3.29 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.30 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

Table 3.33: AC:N regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in AC:N within treatments.

Treatment	Equation	R^2	p. value
Straw	$y = 0.0449x + 4.2461$	$R^2 = 0.0963$	.611
Woodchip	$y = 0.2599x + 1.8392$	$R^2 = 0.8742$	**< .05**
Sheep	$y = 0.1719x + 1.2939$	$R^2 = 0.8691$	**< .05**
Cattle	$y = 0.2404x + 3.5879$	$R^2 = 0.4873$	.190

AC:N ratio increased over time ($p = 0.02$) (Table 3.33) in the woodchip treatment, largely due to the decrease in TSN ($p = 0.04$) (Table 3.31). In contrast the increase in straw AC:N ratio up to week 10 (Figure 3.29) is attributable to the rapid decomposition of compost solids releasing large quantities of organic C into the matrix; the straw AC:N ratio then decreased slightly, which is attributable to DOC being oxidised in greater quantities than TSN is taken up. In cattle composts AC:N ratio (Fig. 3.30) increased rapidly to week 20, and then fell, whereas in sheep it increased only slowly to week 20 and then greatly to week 31.

Potassium (K_2O)



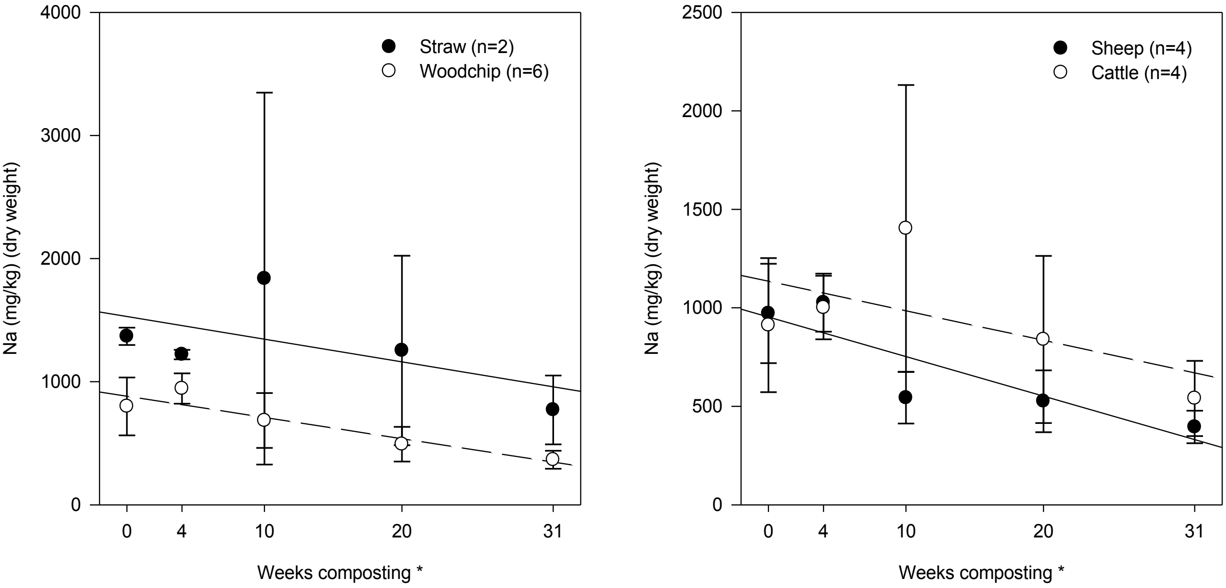
***Figures 3.31 (bedding)** and **3.32 (livestock):** show the relationship between K_2O and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Values represent mean ±1 se. Fig. 3.31 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.32 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

Table 3.34: K_2O regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in K_2O within treatments.

Treatment	Equation	R^2	p. value
Straw	$y = -208.54x + 12327$	$R^2 = 0.6672$	.091
Woodchip	$y = -101.34x + 4679.1$	$R^2 = 0.4005$	.252
Sheep	$y = -115.73x + 5975.4$	$R^2 = 0.5781$	.136
Cattle	$y = -140.54x + 7206.6$	$R^2 = 0.6299$	.109

Figures 3.31 and 3.32 show a non-linear change over time in K_2O concentrations in all treatments. There is an increase during the first 4 to 6 weeks as the labile manure fraction is rapidly broken down, and then a decrease as large quantities are leached in solution. Table 3.34 shows no overall linear relationships between K_2O concentrations and composting time in either bedding material or livestock type, although there are significant decreases ($p <0.05$) in the both bedding treatments, between the start and end of composting (see Figures 3.61 and 3.62). Livestock urine contains large concentrations of highly soluble K_2O (personal communications with D.L. Jones), and as a result, large amounts are easily lost in seepage throughout the composting period.

Sodium (Na)



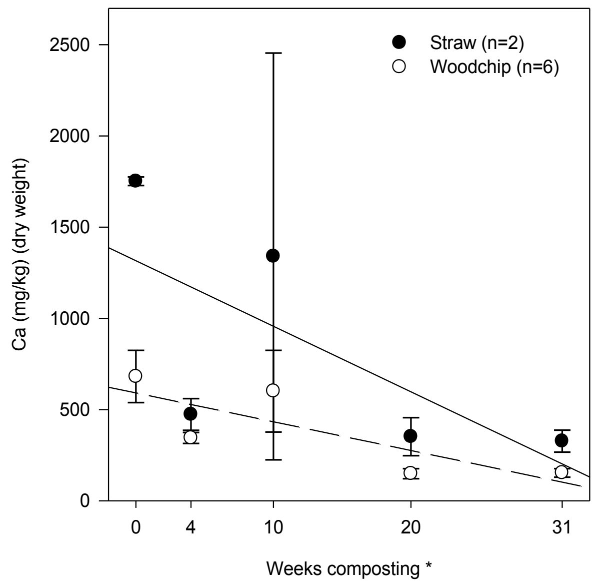
Figures 3.33 (bedding) *and* ***3.34 (livestock):*** *show the relationship between Na and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Values represent mean ±1 se. Fig. 3.33 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.34 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

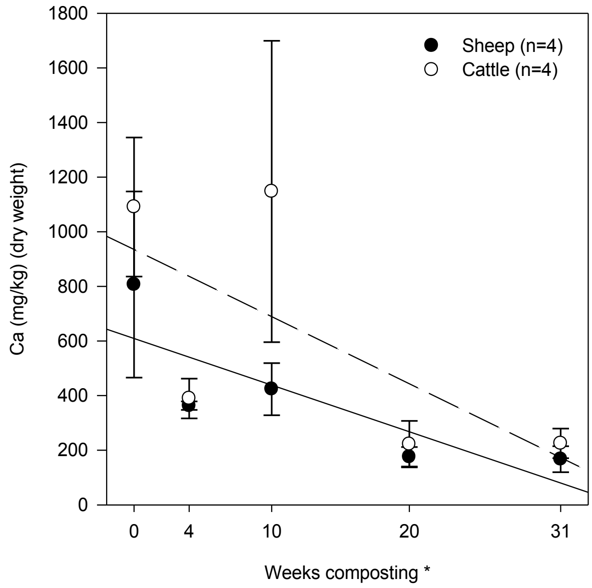
Table 3.35: Na regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in Na within treatments.

Treatment	Equation	R^2	p. value
Straw	y = -18.804x + 1703.7	R² = 0.1281	.554
Woodchip	y = -17.122x + 824.02	R² = 0.6244	.112
Sheep	y = -15.23x + 792.82	R² = 0.8531	**< .05**
Cattle	y = -19.855x + 1295.1	R² = 0.8985	**< .05**

The decrease in concentration of Na in the composts is shown most clearly when the composts of the two livestock treatments are separated (Figures 3.33 and 3.34, Table 3.35). This reflects the difference in quantity and quality of manure added by the two livestock types during housing. Each of the four pens per livestock treatment had equal numbers of animals and a silage diet. Furthermore, Na concentrations tend to be higher in straw composts than woodchip because the B:M ratio is lower; thus a straw compost contains proportionately higher levels of Na kg^{-1}.

Calcium (Ca)





***Figures 3.35 (bedding)** and **3.36 (livestock):** show the relationship between Ca and composting time in bedding materials and livestock types. Solid regression lines relate to Straw and Sheep treatments; dashed regression lines, to Woodchip and Cattle treatments. Values represent mean ±1 se. Fig. 3.35 * data include sheep and cattle composts of different ages; sheep + 2 weeks. Fig. 3.36 * sheep composts are constantly + 2 weeks (wks. 2 to 33) in relation to the cattle timeline depicted.*

Table 3.36: Ca regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in Ca within treatments.

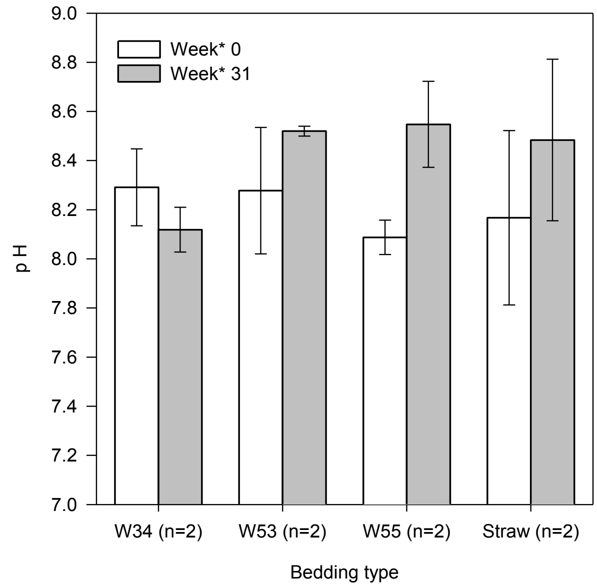
Treatment	Equation	R^2	p. value
Straw	y = -38.931x + 1491.8	$R^2 = 0.3331$	.308
Woodchip	y = -14.767x + 531.68	$R^2 = 0.7315$	.065
Sheep	y = -18.162x + 669.35	$R^2 = 0.5173$	.171
Cattle	y = -23.454x + 874.08	$R^2 = 0.6056$	.121

Initial Ca content, as with initial K and Na content, is strongly influenced by livestock dietary inputs, but the pattern and rate of loss during composting is determined by the physical-chemical characteristics of the bedding-compost. Figures 3.35 and 3.36 show some evidence that Ca concentrations were initially higher in cattle than sheep treatments owing to difference in their excretal inputs, and strong evidence that they were initially much higher in straw than woodchip treatments due to B:M ratio. Concentrations in each bedding type then tended to decrease due to leaching and, to a lesser extent, microbial immobilization over time, though the linear decrease was not significant (Table 3.36) - see section 3.4 for further discussion.

3.3.4.5 Chemical changes between the start and end of composting

The following graphs show change in compost nutrient concentrations between the start (Week* 0) and end (Week* 31) of composting. Week* denotes that the bedding type and bedding material data includes sheep beddings which began composting two weeks earlier than the cattle beddings. The timescale displayed is that of cattle beddings. The sheep data can be viewed as from Week 2 to Week 33 respectively. Symbols displayed above paired columns denote significant (* $p<0.05$; ** $p<0.01$ and *** $p<0.001$) differences in the tested concentrations within the treatment between the start and end of composting; (n=#) displayed after each treatment denotes the number of compost treatments included in the treatment data.

pH and EC



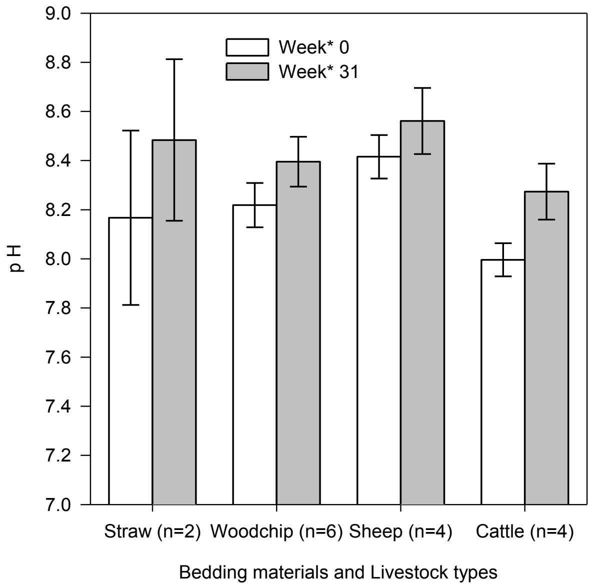
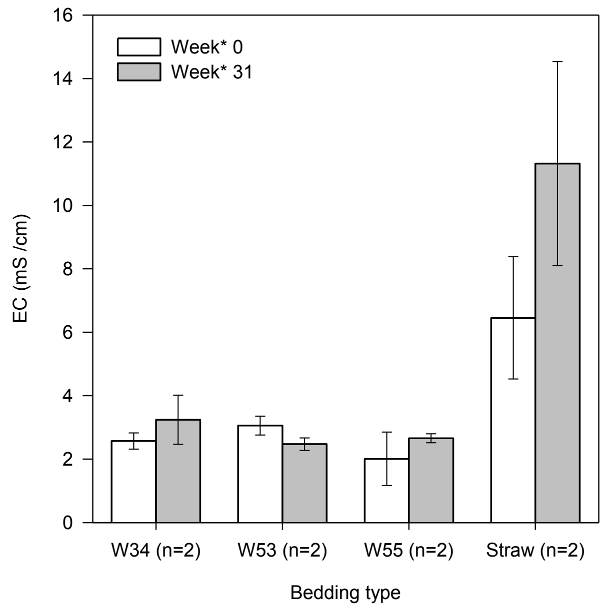


Figure 3.37: *pH in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS. Values represent mean ±1 se.* ***Figure 3.38:*** *pH in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Values represent mean ±1 se. Week* bedding means include sheep and cattle compost data of different ages; sheep +2 weeks.*



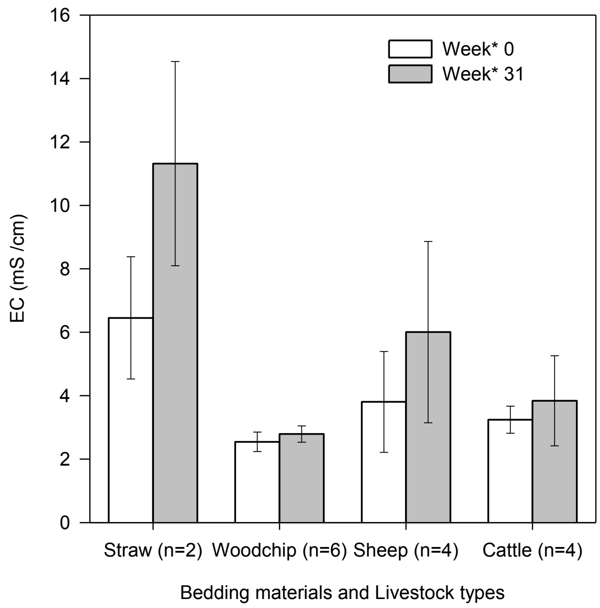
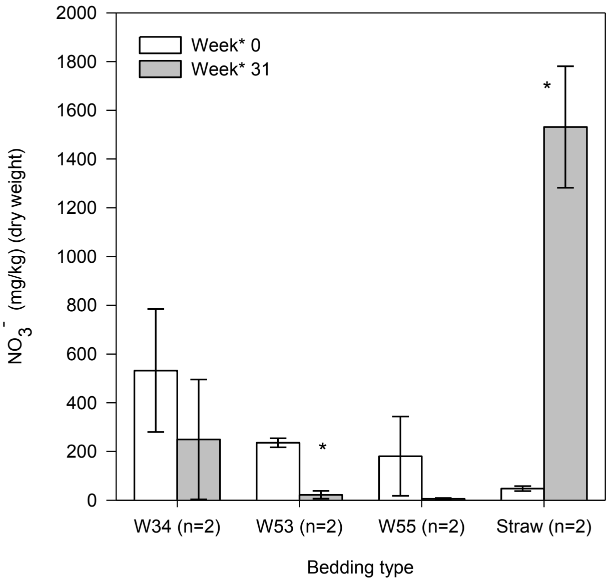
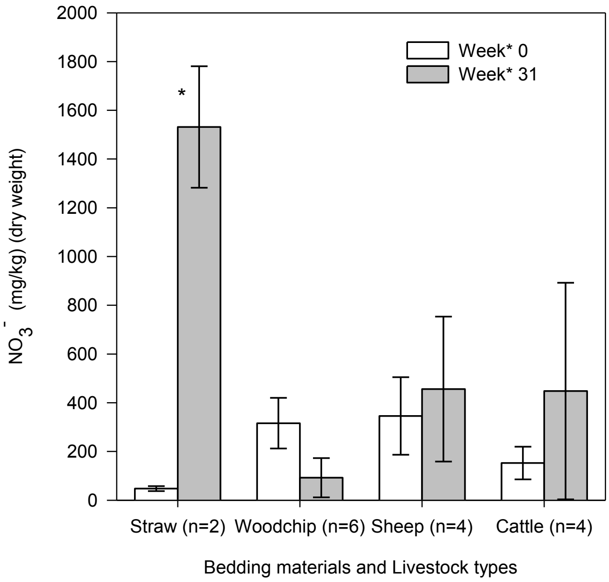


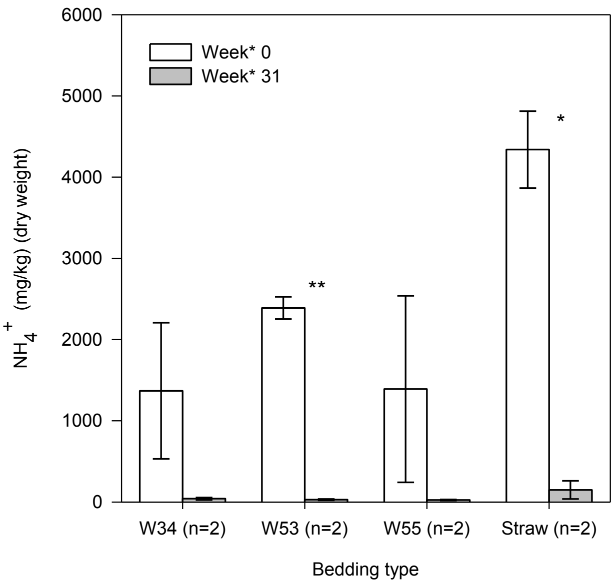
Figure 3.39: *Electrical Conductivity (EC) of each bedding type at the start (white bars) and end (grey bars) of composting at ADAS. Values represent mean ±1 se.* ***Figure 3.40****: EC of bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Values represent mean ±1 se. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks.*

Nitrate and Ammonium





***Figures 3.41:** Nitrate content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS. **Figure 3.42:** Nitrate content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*



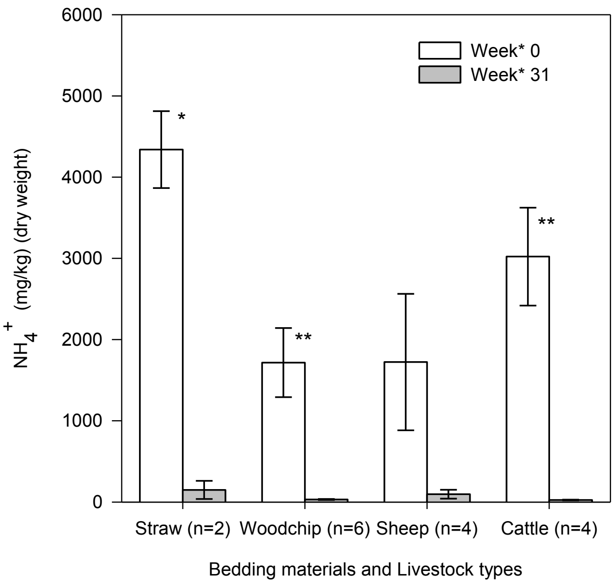
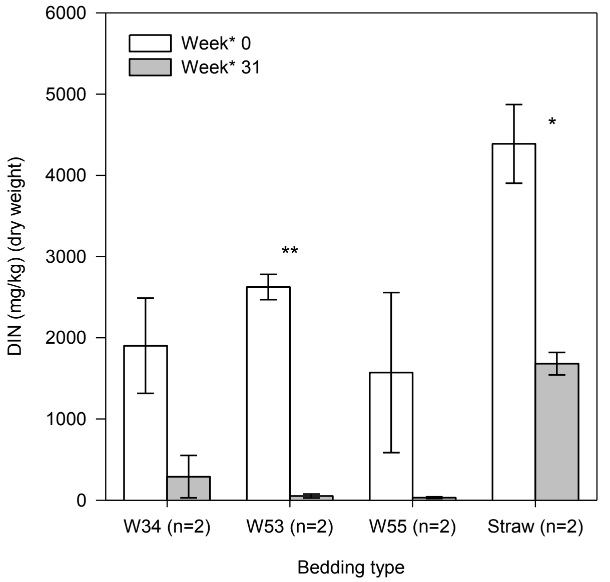


***Figure 3.43:** Ammonium content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS. **Figure 3.44:** Ammonium content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*

DIN and DON



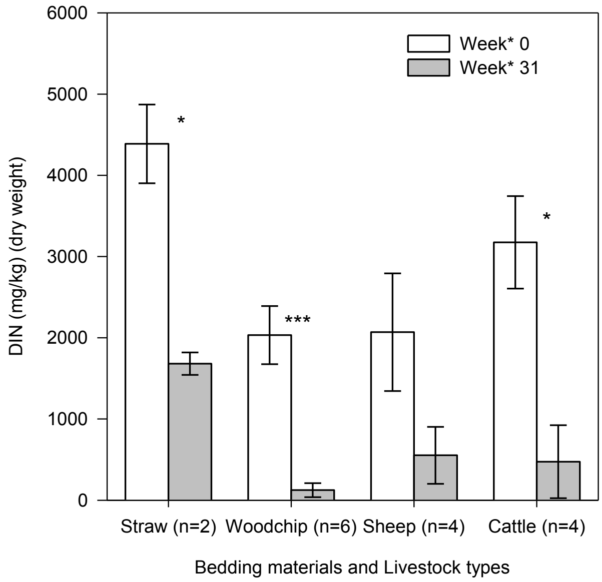
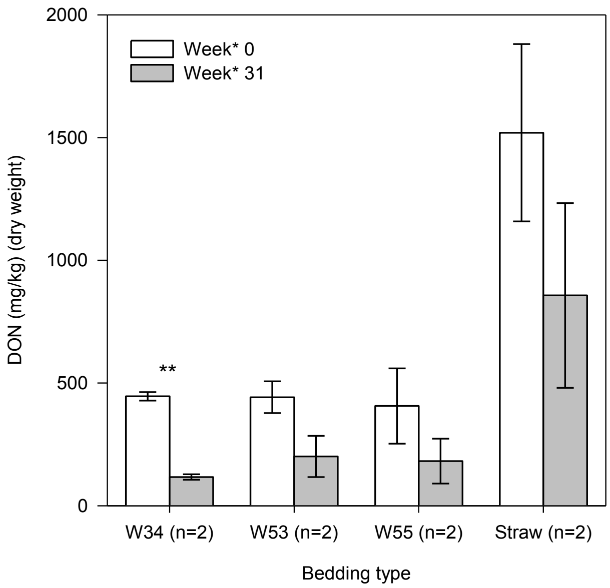


Figure 3.45: *Dissolved inorganic nitrogen (DIN) content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.46:*** *Dissolved inorganic nitrogen (DIN) content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep +2 weeks. Values represent mean ±1 se.*



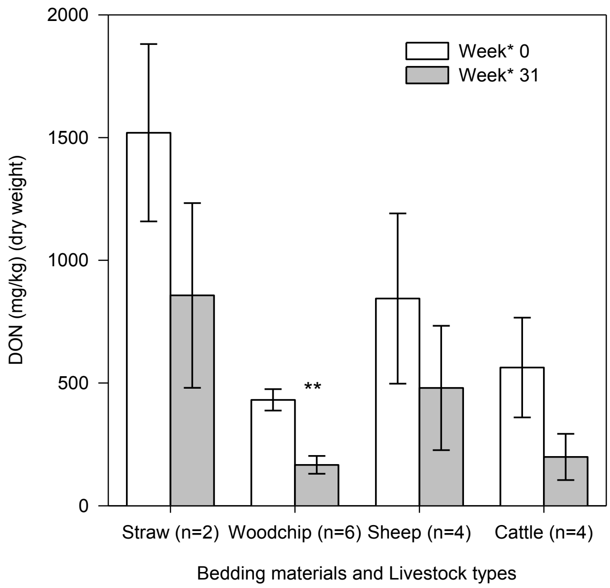
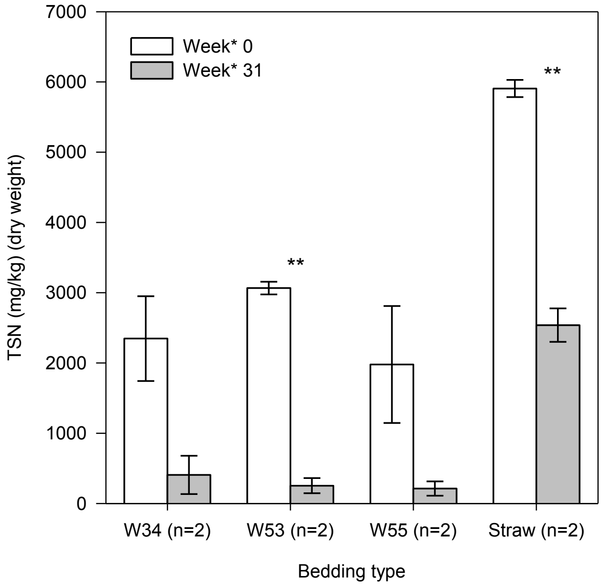


Figure 3.47: *Dissolved organic nitrogen (DON) content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.48:*** *Dissolved organic nitrogen (DON) content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*

TSN and DOC



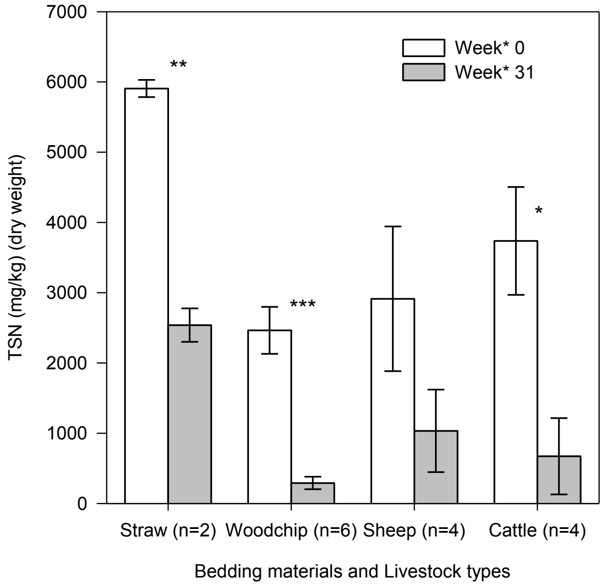
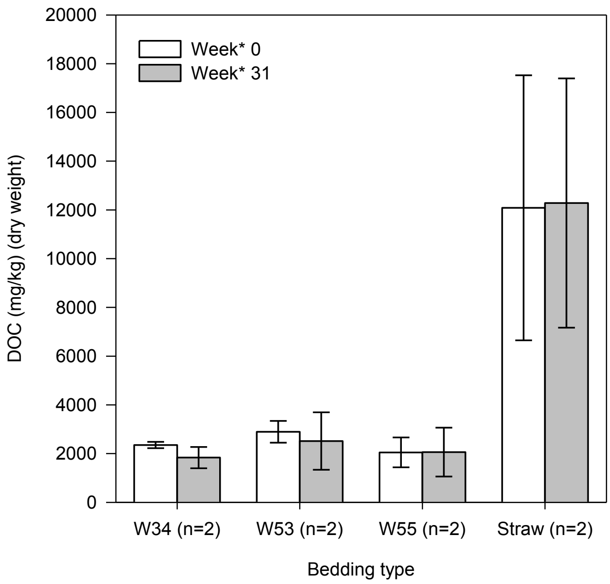


Figure 3.49: *Total soluble nitrogen (TSN) content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.50:*** *Total soluble nitrogen (TSN) content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*



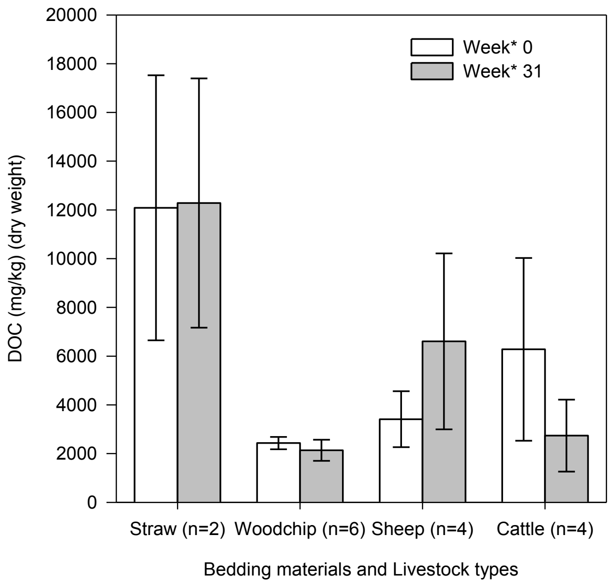
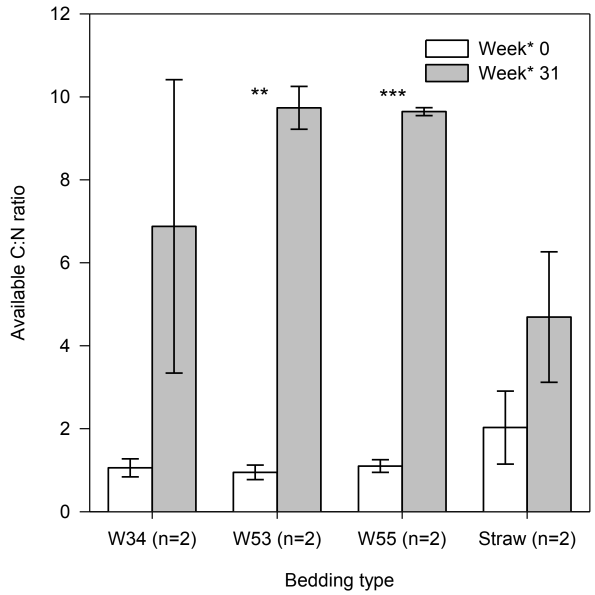


Figure 3.51: *Dissolved organic carbon (DOC) content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.52:*** *Dissolved organic carbon (DOC) content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*

Available C:N and Total C:N



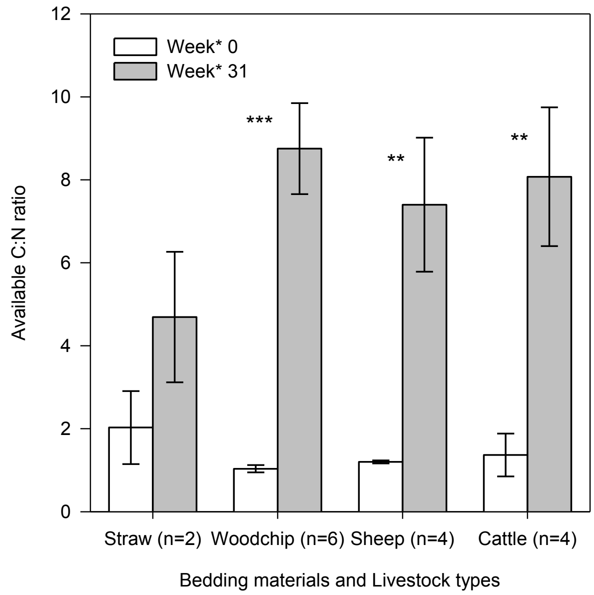
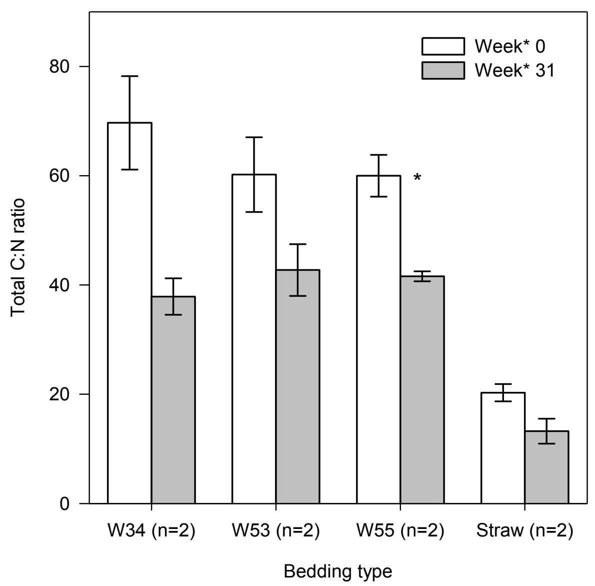


Figure 3.53: *Available C:N ratio in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.54:*** *Available C:N ratio in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep +2 weeks. Values represent mean ±1 se.*



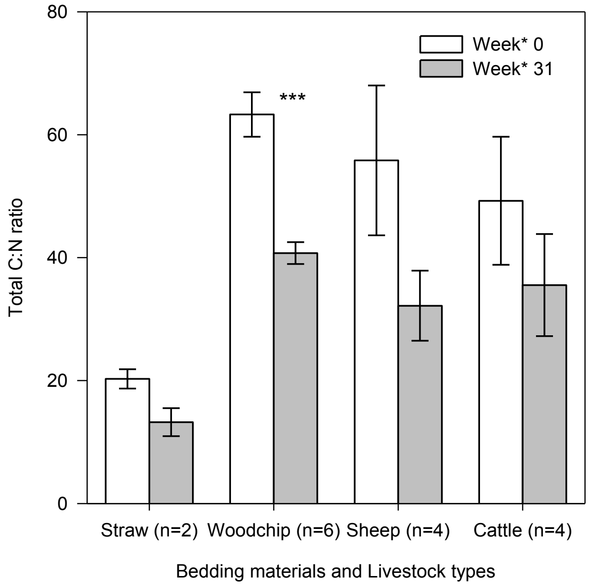
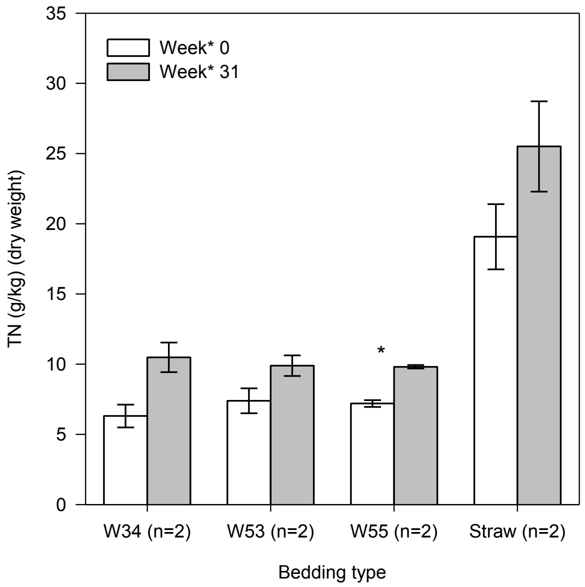


Figure 3.55: *Total C:N ratio in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.56:*** *Total C:N ratio in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep +2 weeks. Values represent mean ±1 se.*

TN and TC



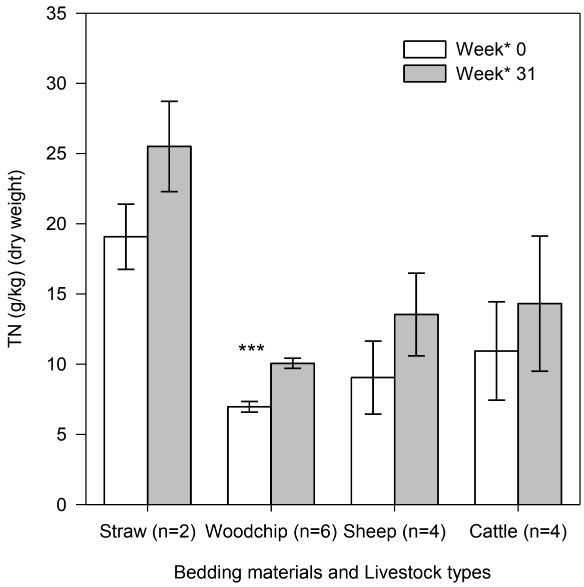
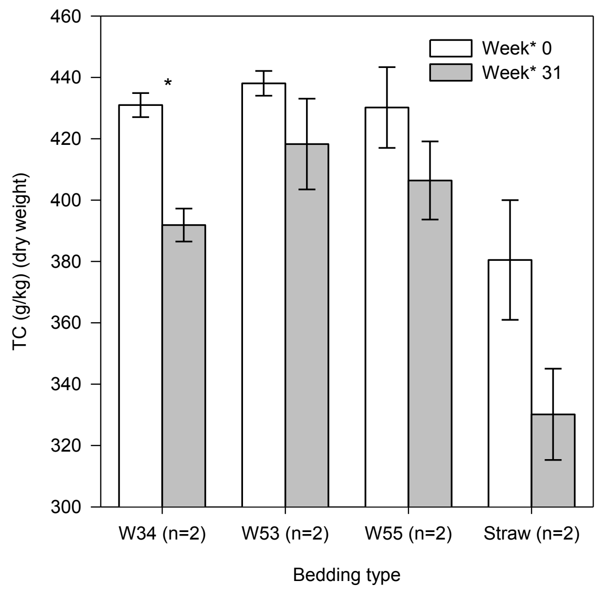


Figure 3.57: *Total N content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.58:*** *Total N content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*

Table 3.37: Percentage of Total N that is available N (AN) at the start and end of composting in each bedding type, bedding material and livestock type at ADAS; Week * denote bedding means include sheep and cattle compost data of different ages; sheep +2 weeks.

ADAS	% of Total N as AN	
Bedding type	Week 0 *	Week 31 *
W34 (n=2)	36.6	3.7
W53 (n=2)	41.9	2.5
W55 (n=2)	27.9	2.2
Straw (n=2)	31.3	10.2

ADAS	% of Total N as AN	
Treatments	Week 0 *	Week 31 *
Straw (n=2)	31.3	10.2
Wood (n=6)	35.5	2. 8
Sheep (n=4)	31.9	6.3
Cattle (n=4)	37.0	3.0



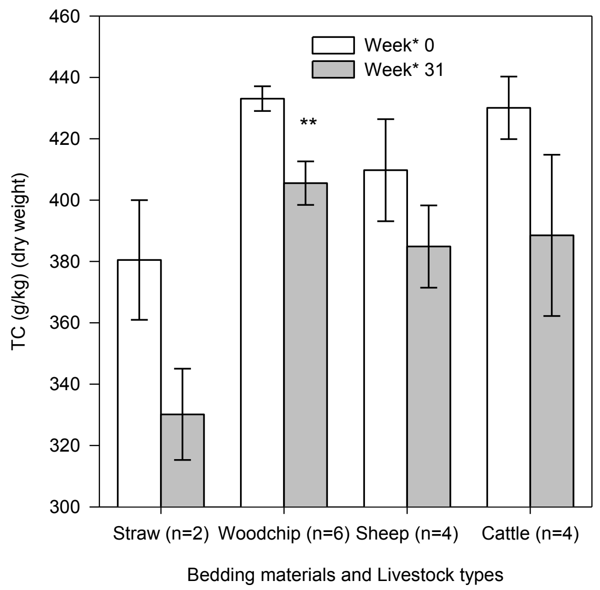
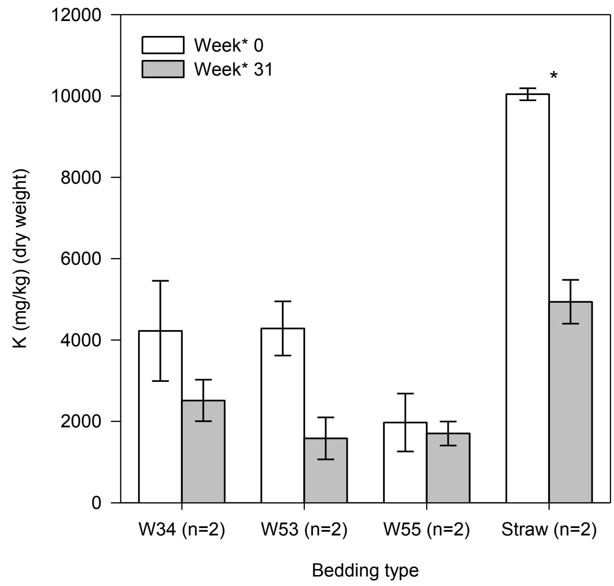


Figure 3.59: *Total C content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.60:*** *Total C content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep +2 weeks. Values represent mean ±1 se.*

Table 3.38: Percentage of Total C that is available C (AC) at the start and end of composting in each bedding type, bedding material and livestock type at ADAS; Week * denote bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks.

ADAS	% of Total C as AC		ADAS	% of Total C as AC	
Bedding type	Week 0 *	Week 31 *	Treatments	Week 0 *	Week 31 *
W34 (n=2)	0.6	0.5	Straw (n=2)	3.1	3.7
W53 (n=2)	0.7	0.6	Wood (n=6)	0.6	0.5
W55 (n=2)	0.5	0.5	Sheep (n=4)	0.9	1.8
Straw (n=2)	3.1	3.5	Cattle (n=4)	1.5	0.8

Potassium and Sodium



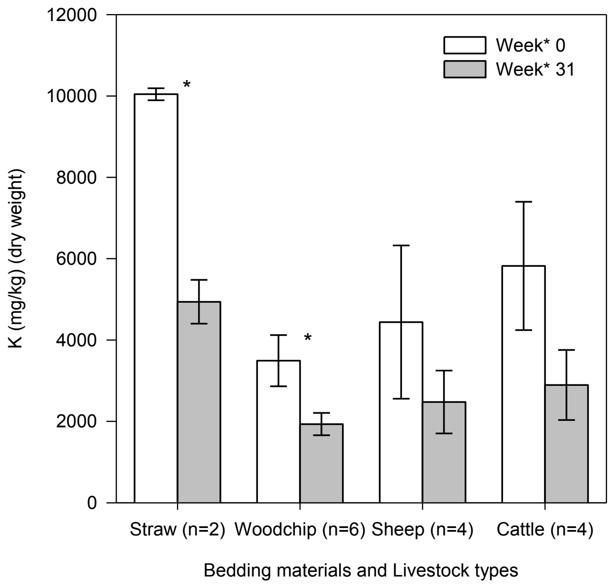
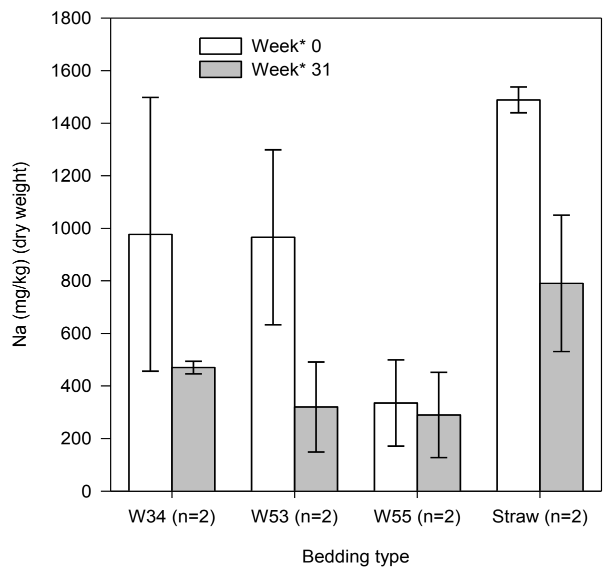


Figure 3.61: *Potassium (K_2O) content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.62:*** *Potassium (K_2O) content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*



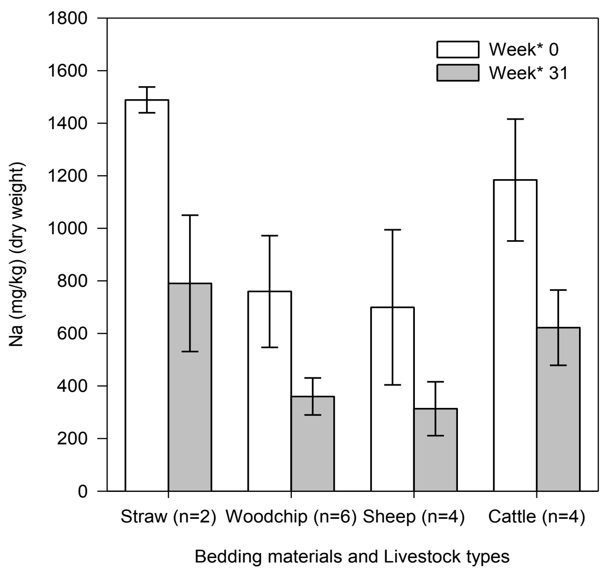
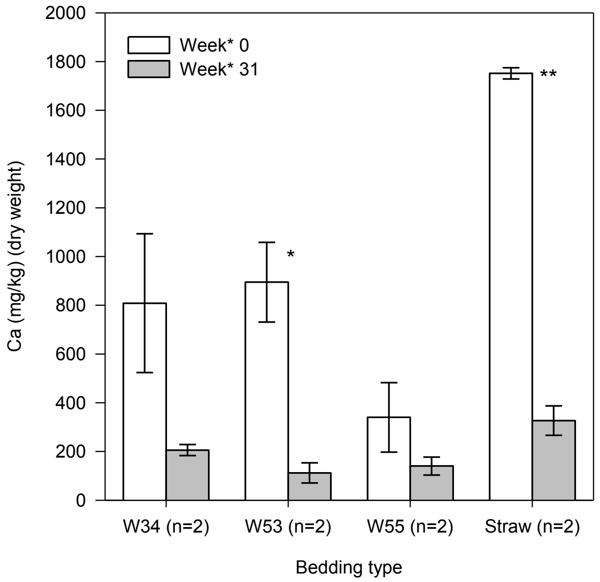


Figure 3.63: *Sodium content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.64:*** *Sodium content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*

Calcium and Available (soluble) P



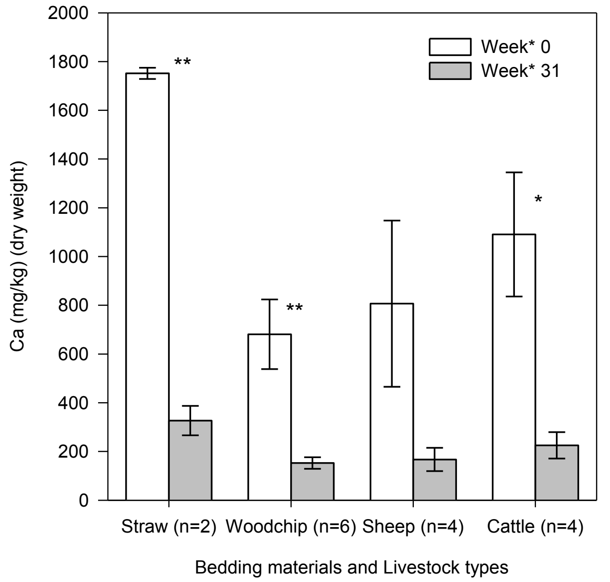
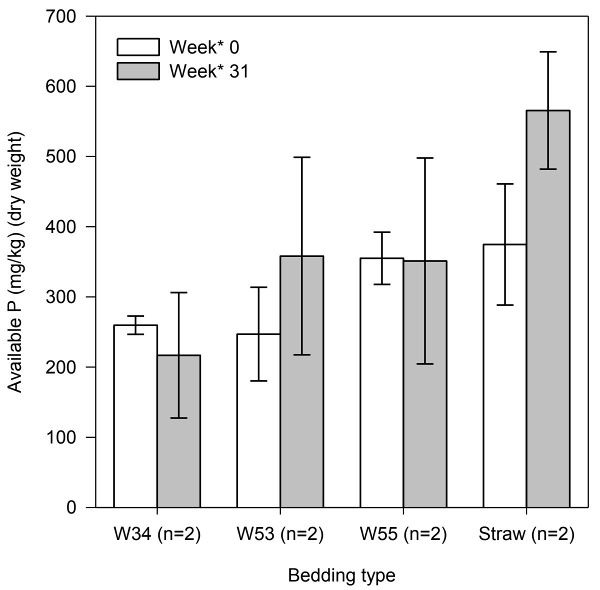


Figure 3.65: *Calcium content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.66:*** *Calcium content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*



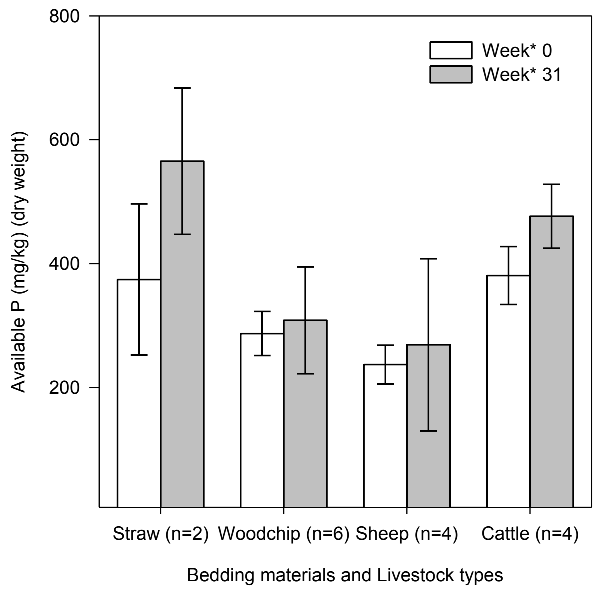


Figure 3.67: *Available (soluble) phosphorus (P_2O_5) content in each bedding type at the start (white bars) and end (grey bars) of composting at ADAS.* ***Figure 3.68:*** *Available (soluble) phosphorus (P_2O_5) content in bedding materials and livestock types at the start (white bars) and end (grey bars) of composting. Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks. Values represent mean ±1 se.*

There was no significant change in pH over the composting period (Figures 3.37 and 3.38), or in soluble salt concentrations (Figures 3.39 and 3.40), which may have been expected in the sheep treatments owing to the volume of water ADAS added to the composts between weeks 3 and 7. NO_3^- increased ($p < 0.05$) in the straw bedding-compost treatment (Figure 3.42) but decreased ($p < 0.05$) in W53 (Figure 3.41), NO_3^- levels also decreased in W34 and W55, but because levels were so low, variations between sample readings increased the error of the mean resulting in $p > 0.05$ for these two treatments. NH_4^+ concentrations decreased, as expected in all treatments. Straw and cattle treatments contained greater NH_4^+ concentrations than sheep and woodchip in week 0* (Figures 3.43 and 3.44), but by week 31* concentrations had reduced significantly ($p < 0.01$ in cattle and woodchip (notably W53) and $p < 0.05$ in straw). Changes in DIN over the composting period (Figures 3.45 and 3.46) followed a very similar pattern to NH_4^+, owing to the relatively small increases in nitrified ammonium-N. All treatments show decreases in DON (Figures 3.47 and 3.48), but only decreases in the woodchip, notably W34 (Figure 3.47), were significant ($p < 0.01$). Likewise, TSN concentrations (Figures 3.49 and 3.50) were predominantly the same as DIN, thus NH_4^+ was the dominant form of AN throughout the composting period - indicating low levels of nitrification followed by loss, either by leaching or by being converted back into NH_4^+ and immobilized.

DOC concentrations (Figures 3.51 and 3.52) appear to remain unchanged, but they do not account for mass loss, so DOC levels will have reduced substantially. Owing to AC:N ratios remaining below 10:1 in woodchip treatments throughout composting (Figures 3.53 and 3.54), decomposition would appear to have been inhibited, as much by a lack of AC, as by a lack of AN. Although there is a significant increase ($p < 0.001$) of TN in the woodchip compost during composting (Figure 3.57), levels remained very low in comparison to straw-based treatments (Figure 3.58), reflecting the high TC concentrations (Figures 3.59 and 3.60) and TC:N (Figures 3.49 and 3.50) still present at the end of composting. Table 3.37 (AN as a % of TN) shows that W34 had a higher percentage of TN as AN at the start and end of composting, indicating that the drier woodchips with greater absorbency capacity had a microbial nutritional advantage over the initially wetter W55 constituted of chips of the same size and shape. In addition, the W53 which contain larger splinter shaped chips, which compacted during bedding to form a more distinct surface layer of manure, had the highest % TN as AN of all three woodchip bedding types at the start of composting but lost this advantage during composting, and the percentage of TN as AN by the end of composting in W53 was in line with the other two woodchip treatments based on absorbency capacity expectations. Table 3.38 (AC as a % of TC) shows a strong contrast in the % of TC as AC in woodchip beddings compared to straw beddings. It is suggested that the AC deficiency in woodchip treatments plays a significant role in limiting microbial activity within these compost-beddings.

Potassium (Figures 3.61 and 3.62) and sodium (Figures 3.63 and 3.64) concentrations deceased in all treatment levels, significantly ($p < 0.05$) when analysed separately in the straw and woodchip bedding materials. This suggests that significant levels of soluble salts were leached from both beddings during composting. Similarly, reductions are seen in concentrations of calcium ($p < 0.01$) in straw and woodchip (Figure 3.65), but so too from cattle and W53 treatments ($p < 0.05$) (Figures 3.65 and 3.66 respectively). Conversely, soluble P levels increased in all treatments except W34 and W55 (Figures 3.67 and 3.68), though changes in soluble P were not significant in any of the treatments.

3.3.4.6 Chemical characterisation of composts at the end of composting

Table 3.39: Mean nutrient contents in each of the ADAS bedding types at the end of the composting, incl. ±1 se and SE of Diff. (Tukey HSD). Letters a, b, c, d; different letters (by row) after treatment data denote difference ($p < 0.05$) in variable concentrations. Identical letter(s) denote ($p > 0.05$).

ADAS Week 31 *	W34 (n=2)		se		W53 (n=2)		se		W55 (n=2)		Se		Straw (n=2)		se		Tukey HSD
pH	8.12	±	0.09	a	8.52	±	0.02	a	8.55	±	0.18	a	8.48	±	0.33	a	0.27
EC mS/cm	3.24	±	0.78	a	2.47	±	0.20	a	2.66	±	0.14	a	11.3	±	3.22	a	2.34
NO_3^- mg/kg	249	±	246	a	22.3	±	15.8	a	5.45	±	3.48	a	1532	±	249	b	248
NH_4^+ mg/kg	40.8	±	15.7	a	29.6	±	8.24	a	25.4	±	6.97	a	150	±	111	a	79.9
DIN mg/kg	290	±	262	a	52.0	±	24.0	a	30.9	±	10.5	a	1682	±	138	b	210
DON mg/kg	117	±	11.1	a	201	±	83.9	a	182	±	91.4	a	857	±	376	a	280
TSN mg/kg	407	±	273	a	253	±	108	a	213	±	102	a	2539	±	238	b	277
DOC mg/kg	1836	±	436	a	2516	±	1181	a	2064	±	1003	a	12282	±	5112	a	3790
AC:N	6.88	±	3.54	a	9.73	±	0.52	a	9.64	±	0.10	a	4.69	±	1.57	a	2.76
K mg/kg	2515	±	511	ab	1583	±	518	a	1704	±	294	a	4941	±	539	b	673
Na mg/kg	470	±	23.8	a	320	±	171	a	290	±	162	a	791	±	260	a	249
Ca mg/kg	206	±	22.9	a	112	±	41.5	a	140	±	37.0	a	327	±	60.4	a	60.3
TN g/kg	10.5	±	1.05	a	9.89	±	0.74	a	9.81	±	0.12	a	25.5	±	3.22	a	2.45
TC g/kg	392	±	5.36	ab	418	±	14.8	a	406	±	12.7	a	330	±	14.9	b	17.8
TC:N	37.9	±	3.34	a	42.7	±	4.74	a	41.6	±	0.91	a	13.2	±	2.28	b	4.45
AP mg/kg	217	±	126	a	358	±	199	a	351	±	208	a	566	±	118	a	237
TP mg/kg	2134	±	63.6	a	2417	±	112	a	2302	±	218	a	5189	±	728	b	545
Cu mg/kg	12.7	±	2.76	a	14.2	±	1.85	a	13.2	±	1.86	a	29.0	±	10.9	a	8.16
Zn mg/kg	99.5	±	17.0	a	146	±	24.3	a	121	±	1.61	a	193	±	25.7	a	27.8

Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks.

Table 3.39 shows no significant differences ($p > 0.05$) in nutrient concentrations between the three woodchip composts in the ADAS experiment after composting. However, the W34 treatment contains higher mean levels of NO_3^-, NH_4^+ (and consequently, TSN), K, Na and Ca, and lower concentrations of soluble P, DON, DOC, TC (and consequently lower AC:N and TC:N) than W53 and W55. This contrasting nutrient profile indicates marginally greater microbial activity during composting in the initially drier W34, which is supported by the compost temperature data shown in Figures 3.1 and 3.2. It is also interesting to note that the contrast in nutrient levels between W53 and W55 bedding at the start of composting (see Table 3.23), which is considered to be attributable to the differences in age and shape of the chips, has greatly diminished.

AC:N ratios in all four bedding types in the ADAS experiment are < 10:1 (Table 3.39), but for opposite reasons. Straw composts have excess AN (in relation to AC) and so are prone to N loss, whereas woodchip treatments are deficient in both AC and AN, resulting in microbial immobilization of N. This supposition is supported by the estimated N budgets presented in section 3.3.6 which show the percentages of N lost from straw and woodchip during composting.

Table 3.40: Mean nutrient contents in ADAS bedding material and livestock treatments at the end of composting, incl. ±1se. Symbols displayed between treatment data represent significant (* p<0.05; ** p<0.01 and *** p<0.001) differences in variable concentrations between treatment pairs.

ADAS	Wood				Straw			Sheep				Cattle		
Week 31*	(n=6)		se		(n=2)		se	(n=4)		se		(n=4)		se
pH	8.40	±	0.10		8.48	±	0.33	8.56	±	0.10		8.27	±	0.10
EC mS/cm	2.79	±	0.26	**	11.32	±	3.22	6.01	±	2.90		3.84	±	1.40
NO_3^- mg/kg	92.4	±	80.8	**	1532	±	249	456	±	297		448	±	444
NH_4^+ mg/kg	32.0	±	5.72	*	150	±	111	97.1	±	55.0		25.9	±	4.43
DIN mg/kg	124	±	85.9	***	1682	±	138	553	±	350		474	±	448
DON mg/kg	167	±	35.9	**	857	±	376	480	±	254		199	±	94.2
TSN mg/kg	291	±	88.5	***	2539	±	238	1033	±	587	*	673	±	543
DOC mg/kg	2138	±	434	**	12282	±	5112	6607	±	3607		2741	±	1478
AC:N	8.75	±	1.10		4.69	±	1.57	7.40	±	1.60		8.07	±	1.67
K mg/kg	1934	±	274	**	4941	±	539	2476	±	771		2896	±	862
Na mg/kg	360	±	70.6	*	791	±	260	314	±	103	*	622	±	143
Ca mg/kg	153	±	23.5	*	327	±	60.4	167	±	47.5		225	±	54.4
TN g/kg	10.1	±	0.36	***	25.5	±	3.22	13.5	±	2.90		14.3	±	4.81
TC g/kg	406	±	7.11	**	330	±	14.9	385	±	13.4		388	±	26.3
TC:N	40.7	±	1.78	***	13.2	±	2.28	32.2	±	5.70		35.5	±	8.30
AP mg/kg	309	±	86.1		566	±	118	269	±	139		477	±	51.5
TP mg/kg	2284	±	83.6	***	5189	±	728	2818	±	556		3203	±	909
Cu mg/kg	13.4	±	1.02	*	29.0	±	10.9	12.9	±	1.80		21.6	±	6.08
Zn mg/kg	122	±	11.4	*	193	±	25.7	156	±	24.3		123	±	17.4

Week* bedding means include sheep and cattle compost data of different ages; sheep + 2 weeks.

Table 3.40 shows the contrast in nutrient concentrations between wood and straw-based composts in the ADAS experiment and highlights critical deficiencies within the woodchip bedding after composting, especially in TSN and DOC, but the significant difference in TC:N ratios (13:1 in straw and 41:1 in woodchip) is perhaps the most influential result, caused by the inhibitive consequences to microbial functioning at ratios < 40:1 (Bernal; 2009). Furthermore, the results illustrate the dominant influence of bedding type, compared to livestock inputs: sheep compost TSN concentrations are significantly ($p < 0.05$) greater than in cattle composts, whereas cattle Na concentrations are significantly ($p < 0.05$) greater than in sheep composts.

3.3.5 Chemical changes during housing and composting at IGER

3.3.5.1 Chemical characterisation of raw beddings

Table 3.41: Mean nutrient contents in each of IGER's raw beddings types, including both woodchip deliveries (Wc1 and Wc2)) and raw materials, incl. ±1 se. Letters a, b, c, d; different letters (by row) after bedding type data denotes difference ($p < 0.05$) in concentrations. Identical letter(s) denote ($p > 0.05$). Symbols displayed between bedding material data represent (* $p<0.05$; ** $p<0.01$ and *** $p<0.001$) differences in concentrations.

IGER	Wc1				Wc2				Straw				Tukey	mean Wc				Straw		
Raw Bedding	(n=4)		se		(n=4)		se		(n=4)		se		HSD	(n=8)		se		(n=4)		se
pH	3.11	±	0.13	a	3.33	±	0.08	a	7.49	±	0.12	b	.159	3.22	±	0.08	***	7.49	±	0.12
EC mS/cm	0.13	±	0.02	a	0.10	±	0.01	a	3.70	±	0.40	b	.327	0.12	±	0.01	***	3.70	±	0.40
NO_3^- mg/kg	2.65	±	1.55	a	0.86	±	0.86	a	0.00	±	0.00	a	1.45	1.76	±	0.89		0.00	±	0.00
NH_4^+ mg/kg	0.57	±	0.20	a	0.28	±	0.14	a	30.7	±	1.91	b	1.58	0.43	±	0.13	***	30.7	±	1.91
DIN mg/kg	3.22	±	1.47	a	1.14	±	0.77	a	30.7	±	1.91	b	2.07	2.18	±	0.86	***	30.7	±	1.91
DON mg/kg	20.2	±	8.72	a	25.7	±	5.00	a	234	±	24.2	b	21.4	23.0	±	4.77	***	234	±	24.2
TSN mg/kg	23.5	±	10.2	a	26.8	±	5.37	a	265	±	23.6	b	21.6	25.2	±	5.37	***	265	±	23.6
DOC mg/kg	1438	±	290	a	1359	±	211	a	3902	±	399	b	438	1399	±	167	***	3902	±	399
AC:N	175	±	89.2	a	58.3	±	15.3	a	14.8	±	1.42	a	73.9	117	±	47.4		14.8	±	1.42
K mg/kg	157	±	19.9	a	149	±	10.9	a	6383	±	572	b	467	153	±	10.6	***	6383	±	572
Na mg/kg	25.5	±	2.08	a	25.6	±	2.29	a	536	±	134	b	109	25.5	±	1.43	***	536	±	134
Ca mg/kg	5.35	±	0.91	a	4.77	±	1.18	a	51.5	±	2.62	b	2.46	5.06	±	0.70	***	51.5	±	2.62
AP mg/kg	7.62	±	0.21	a	7.73	±	0.34	a	11.1	±	0.67	b	.643	7.68	±	0.19	***	11.1	±	0.67
TP mg/kg	967	±	8.44	a	847	±	102	a	3088	±	236	b	210	907	±	54.2	***	3088	±	236
TN g/kg	1.52	±	0.16	a	1.30	±	0.05	a	5.45	±	0.09	b	.156	1.41	±	0.09	***	5.45	±	0.09
TC g/kg	483	±	0.40	a	477	±	9.54	a	443	±	7.08	a	9.64	480	±	4.26	**	443	±	7.08
TC:N	322	±	34.2	a	366	±	6.61	a	81.3	±	2.68	b	28.7	344	±	19.1	**	81.3	±	2.68
Cu mg/kg	3.15	±	0.08	a	3.00	±	0.07	a	3.04	±	0.34	a	.291	3.08	±	0.06		3.04	±	0.34
Zn mg/kg	30.3	±	0.34	a	25.1	±	1.44	a	5.06	±	0.65	b	1.32	27.7	±	1.64	**	5.06	±	0.65

Table 3.41 shows significant differences between raw straw and woodchip bedding and the similarity of IGER's two woodchip deliveries.

3.3.5.2 Actual change in nutrient concentrations during the IGER housing trial

Table 3.42: Actual change in nutrient concentrations during IGER's housing period within each bedding, feed and livestock treatment, incl. ±1 se. Symbols displayed between paired treatment types represent (* p<0.05; ** p<0.01 and *** p<0.001) differences in variable concentrations.

IGER Housing	Straw (n=4)	se		Wood (n=4)	se	Silage (n=4)	se		Hay (n=4)	se	Sheep (n=4)	se		Cattle (n=4)	se
pH	0.93	± 0.05	***	5.20	± 0.07	3.12	± 1.23		3.01	± 1.23	3.14	± 1.24	*	2.99	± 1.22
EC mS/cm	3.76	± 1.37		4.17	± 0.61	4.11	± 0.79		3.82	± 1.28	5.60	± 0.41	*	2.33	± 0.57
NO_3^- mg/kg	70.9	± 11.7	**	19.0	± 4.3	56.5	± 19.7	*	33.4	± 11.2	51.3	± 18.3		38.7	± 15.6
NH_4^+ mg/kg	2544	± 521		1422	± 102	2211	± 403		1756	± 543	2231	± 541		1735	± 397
DIN mg/kg	2615	± 527		1441	± 102	2267	± 421		1789	± 550	2283	± 556		1774	± 407
DON mg/kg	1408	± 509		1201	± 309	1490	± 416		1119	± 406	1954	± 223	**	655	± 174
TSN mg/kg	4023	± 939		2642	± 318	3757	± 577		2908	± 921	4237	± 750		2429	± 441
DOC mg/kg	9350	± 970	**	2946	± 187	6576	± 2209		5720	± 1676	6968	± 2248		5327	± 1519
AC:N	-11.1	± 0.84	***	-53.9	± 0.24	-32.9	± 12.3		-32.1	± 12.5	-33.1	± 12.1		-31.9	± 12.6
K mg/kg	3383	± 1152		4885	± 916	5411	± 1044		2858	± 605	3881	± 799		4387	± 1364
Na mg/kg	2891	± 338		1682	± 258	2424	± 380		2150	± 518	2074	± 381		2499	± 499
Ca mg/kg	1831	± 237	*	949	± 166	1584	± 315		1197	± 299	1225	± 242		1555	± 370
TN g/kg	15.5	± 1.21	**	4.73	± 0.47	10.8	± 3.66		9.40	± 2.69	10.9	± 3.20		9.31	± 3.21
TC g/kg	-47.1	± 3.95		-38.7	± 2.42	-44.5	± 3.11		-41.4	± 4.69	-42.0	± 4.63		-43.9	± 3.35
TC:N	-62.1	± 1.34	***	-267	± 4.83	-164	± 58.2		-165	± 60.2	-169	± 61.0		-160	± 57.3
AP mg/kg	426	± 20.7	**	263	± 23.2	325	± 60.4		365	± 38.7	354	± 63.5		335	± 36.3

Table 3.42 shows that during housing, pH significantly increased in woodchip treatments compared to straw owing to the buffering effect of manure, but that AC:N and TC:N ratios (p <0.001); NO_3^-, DOC, TN, and soluble P (p <0.01); and Ca (p <0.05) all increased by a significantly greater amount in straw than woodchip treatments. In contrast pH, EC (p <0.05) and DON (p <0.01) increased by a significantly greater amount in sheep than cattle treatments, and NO_3^- (p <0.05) in silage than hay treatments.

3.3.5.3 Chemical characterisation of treatments at the start of composting

Table 3.43: Nutrient concentrations at week 1 in IGER's bedding, feed and livestock treatments, incl. ±1 se. Symbols displayed between paired treatment types represent (* p<0.05; ** p<0.01 and *** p<0.001) differences in variable concentrations.

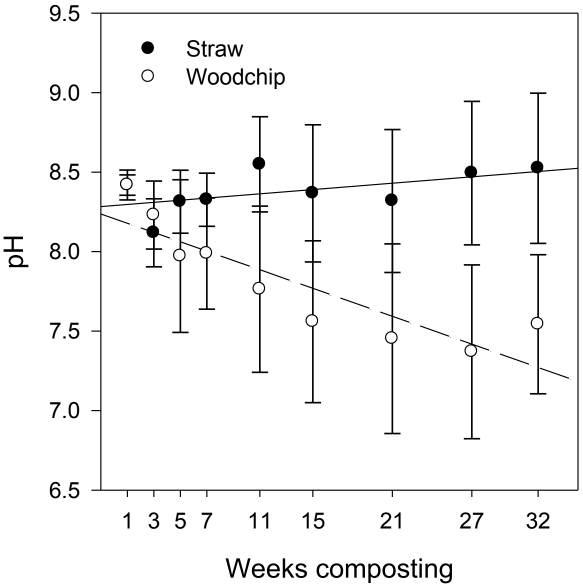
IGER Week 1	Straw (n=4)		se		Wood (n=4)		se	Silage (n=4)		se		Hay (n=4)		se	Sheep (n=4)		se		Cattle (n=4)		se
pH	8.42	±	0.05		8.42	±	0.07	8.47	±	0.06		8.36	±	0.03	8.49	±	0.05	*	8.35	±	0.03
EC mS/cm	7.46	±	1.37	*	4.29	±	0.61	6.02	±	1.13		5.73	±	1.62	7.51	±	1.32	*	4.24	±	0.64
NO_3^- mg/kg	70.9	±	11.7	**	20.8	±	4.26	57.4	±	19.2	*	34.3	±	10.7	52.1	±	17.9		39.5	±	15.1
NH_4^+ mg/kg	2575	±	521		1423	±	102	2226	±	411		1772	±	548	2247	±	550		1751	±	400
DIN mg/kg	2646	±	527		1444	±	102	2284	±	429		1806	±	554	2299	±	564		1790	±	410
DON mg/kg	1642	±	509		1224	±	309	1619	±	418		1247	±	430	2083	±	277	**	783	±	159
TSN mg/kg	4288	±	939		2667	±	318	3902	±	626		3053	±	953	4382	±	818		2574	±	455
DOC mg/kg	13252	±	970	***	4344	±	187	9226	±	2898		8370	±	2383	9619	±	2957		7978	±	2238
AC:N	3.61	±	0.84		1.71	±	0.24	2.23	±	0.49		3.09	±	1.00	2.04	±	0.30		3.28	±	1.01
K mg/kg	9767	±	1152	*	5039	±	916	8679	±	1470		6127	±	1626	7150	±	1442		7656	±	1942
Na mg/kg	3427	±	338	*	1708	±	258	2705	±	468		2430	±	665	2355	±	495		2780	±	631
Ca mg/kg	1883	±	237	*	954	±	166	1612	±	324		1225	±	312	1254	±	254		1583	±	380
TN g/kg	20.9	±	1.21	***	6.14	±	0.47	14.2	±	4.83		12.8	±	3.82	14.3	±	4.36		12.74	±	4.33
TC g/kg	396	±	3.95	**	441	±	2.42	417	±	12.4		420	±	14.2	419	±	14.1		417	±	12.6
TC:N	19.1	±	1.34	***	72.9	±	4.83	46.1	±	16.5		46.0	±	15.3	41.8	±	13.9		50.2	±	17.4
AP mg/kg	437	±	20.7	**	271	±	23.2	334	±	61.4		374	±	39.7	363	±	64.5		345	±	37.3

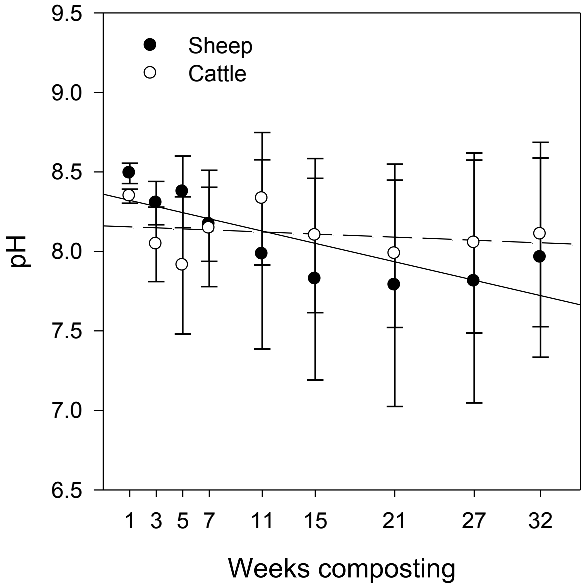
Table 3.43 shows that at the start of composting (week 1) the straw composts contained significantly higher levels of soluble salts, NO_3^-, K, Na, Ca, soluble P (and thus EC), as well as greater DOC, TN, TC and lower TC:N ratio than woodchip-based composts. Differences between feed and livestock treatments match the increases during housing shown in Table 3.42.

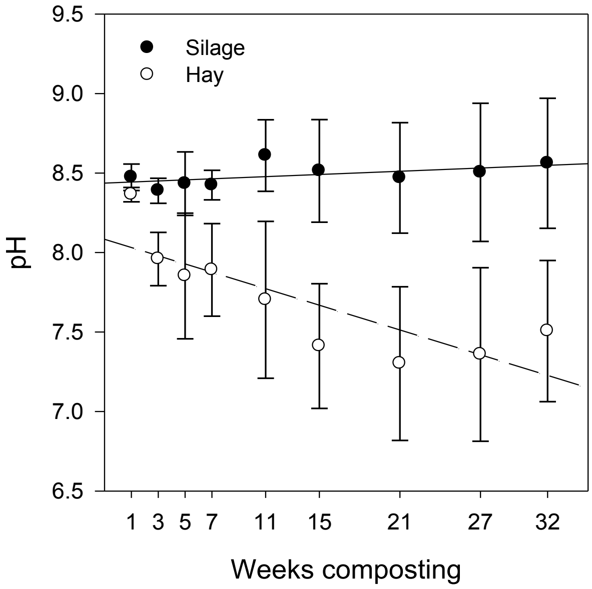
3.3.5.4 Chemical changes during composting - Linear regression analysis

Regression analysis of pH, EC, NO_3^-, NH_4^+, DIN, DON, TSN, DOC, AC:AN, K_2O, Na, and Ca within IGER bedding, livestock and feed types; individual bedding treatments are shown in Appendix VII. Similar to the ADAS results, a linear regression analysis was satisfactory for most nutrient profiles, with the exception of NO_3^-, NH_4^+, DIN and TSN profiles; specific details of each analysis are described where appropriate. Treatment (n= #) is not shown in each graph because each treatment data consists of four (n=4) compost heap means (see Table 3.12 for full details).

pH







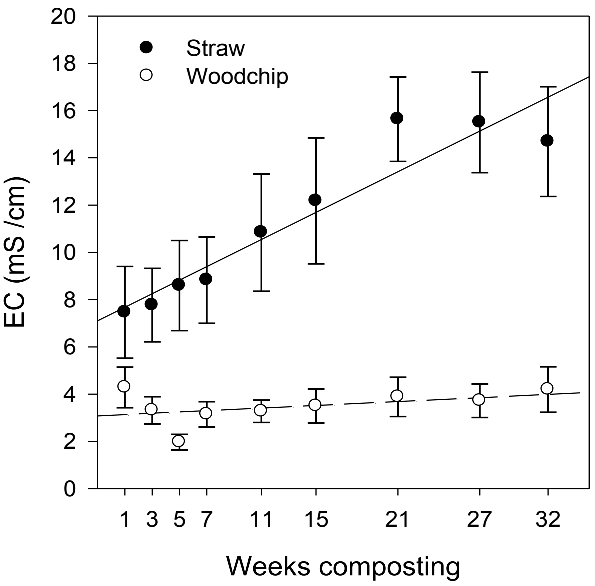
Figures 3.69 (bedding) 3.70 (livestock) *and* ***3.71 (feed)*** *show the relationship between pH and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, white dot treatment icons. Values represent mean ±1 se.*

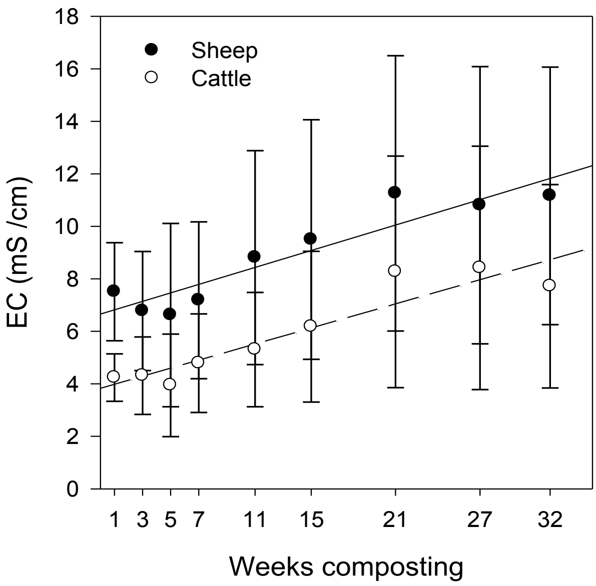
Table 3.44: pH regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in pH within treatments.

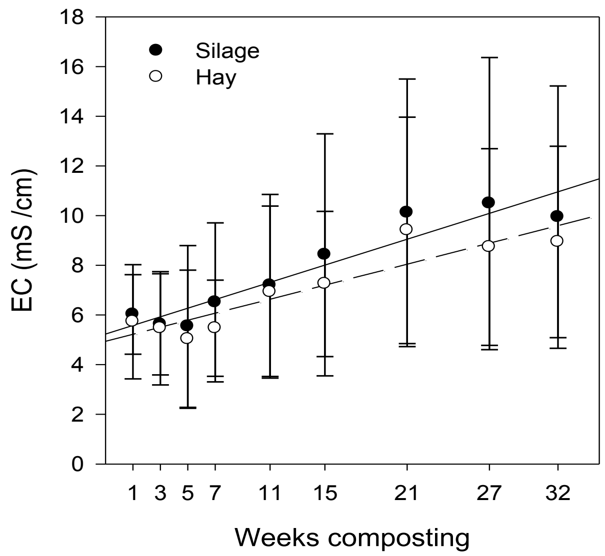
Treatment	Equation	R^2	p. value
Straw	$y = 0.0067x + 8.2904$	$R^2 = 0.3018$	.126
Woodchip	$y = -0.0292x + 8.2072$	$R^2 = 0.7807$	**< .01**
Silage	$y = 0.0034x + 8.4405$	$R^2 = 0.2870$	.137
Hay	$y = -0.0259x + 8.0571$	$R^2 = 0.6781$	**< .01**
Sheep	$y = -0.0193x + 8.34$	$R^2 = 0.6454$	**< .01**
Cattle	$y = -0.0032x + 8.1576$	$R^2 = 0.0606$	.523

Table 3.44 shows pH decreased linearly in woodchip, whereas Figure 3.69 shows a slight increase in straw composts. Figure 3.70 shows a non-linear response (decrease then increase) in sheep, but no clear trend over time in cattle composts. Figure 3.71 also shows a non-linear response (decrease then increase) in hay, whereas pH shows a slight tendency to linear increase in silage composts.

EC







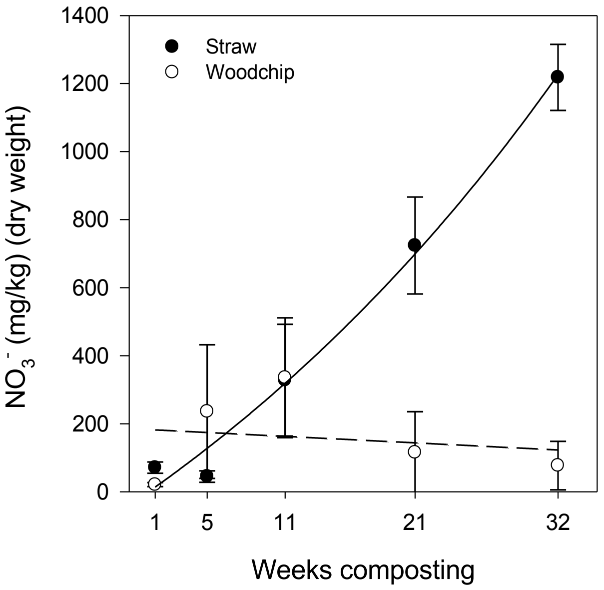
Figures 3.72 (bedding) 3.73 (livestock) *and* ***3.74 (feed):*** *show the relationship between EC and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. Values represent mean ±1 se.*

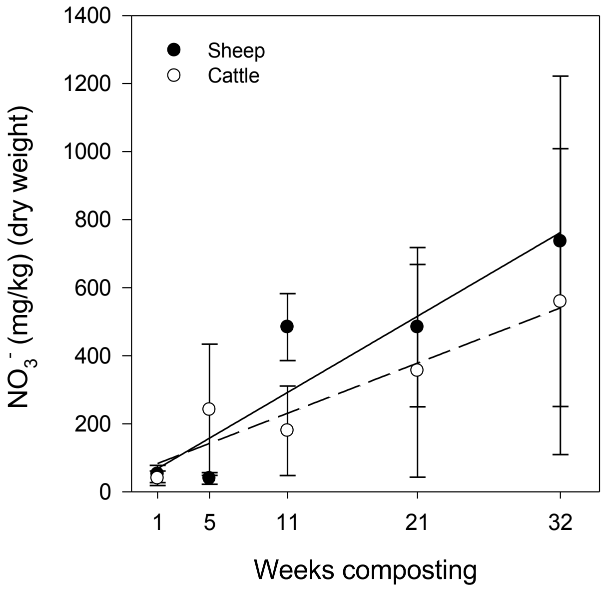
Table 3.45: EC regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in EC within treatments.

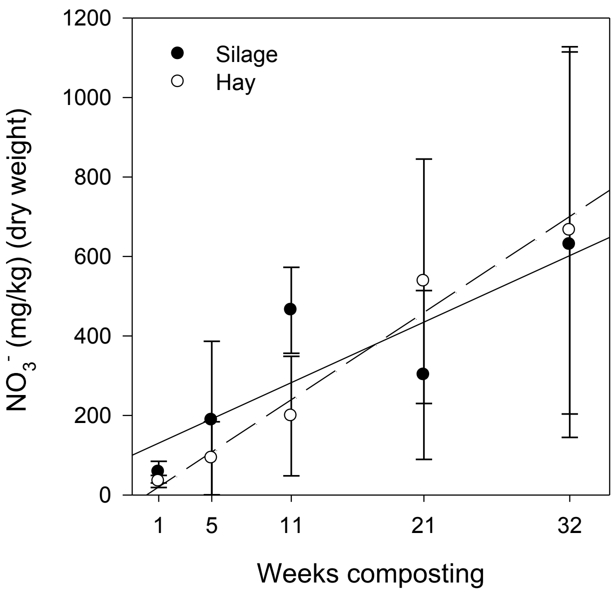
Treatment	**Equation**	R^2	**p. value**
Straw	$y = 0.287x + 7.3858$	$R^2 = 0.8929$	**< .001**
Woodchip	$y = 0.0275x + 3.104$	$R^2 = 0.1907$	.240
Silage	$y = 0.1736x + 5.407$	$R^2 = 0.8971$	**< .001**
Hay	$y = 0.1409x + 5.0828$	$R^2 = 0.8426$	**< .001**
Sheep	$y = 0.1614x + 6.6579$	$R^2 = 0.8650$	**< .001**
Cattle	$y = 0.1531x + 3.8319$	$R^2 = 0.8743$	**< .001**

Table 3.45 shows that salt EC content increased significantly during composting in all treatments except woodchip ($p <0.001$) (Figures 3.72, 3.73 and 3.74). In woodchip composts EC remained much more stable, though did show a slight tendency to increase.

Nitrate







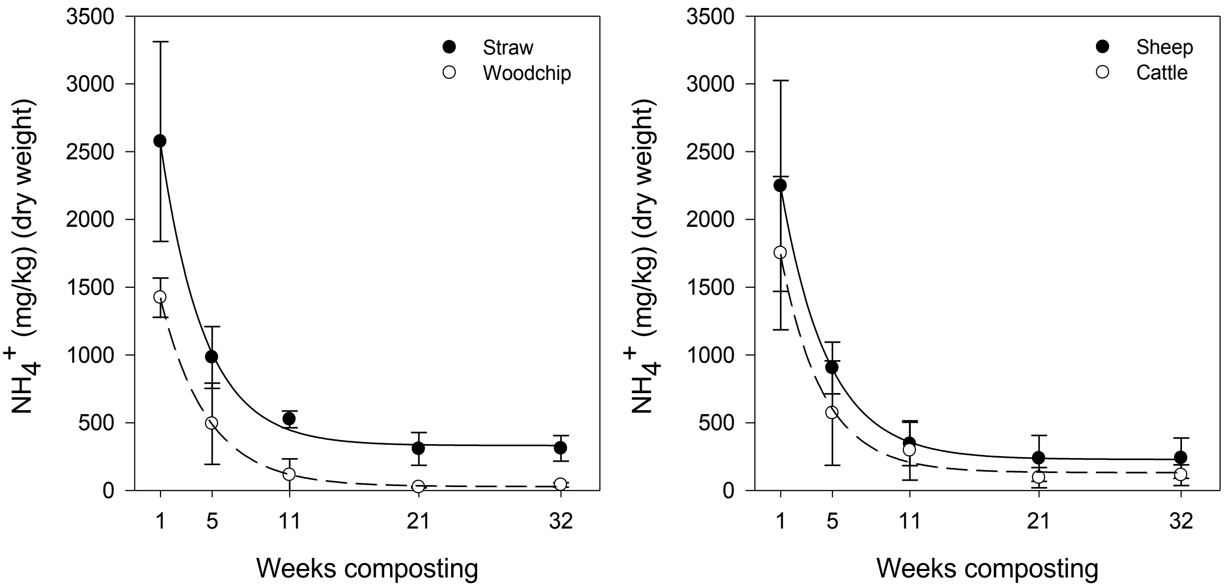
Figures 3.75 (bedding) 3.76 (livestock) *and* ***3.77 (feed):*** *show the relationship between* NO_3^- *and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons.* NO_3^- *in straw is analysed using an exponential growth curve (3 parameters) f = y0+a*exp(b*x). Values represent mean ±1 se.*

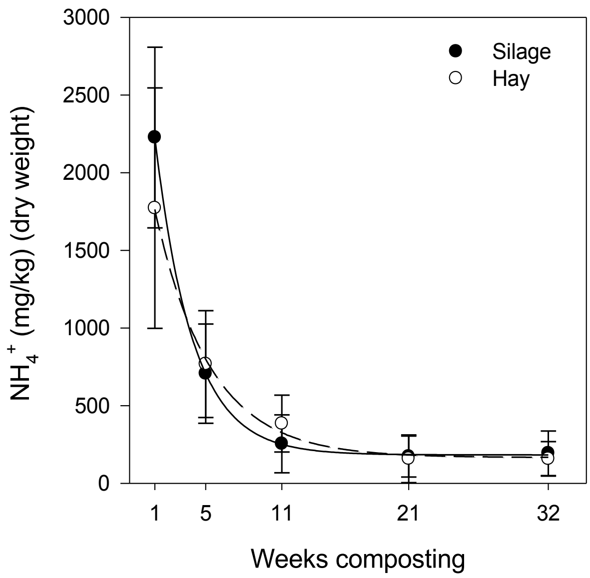
Table 3.46: NO_3^- regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in NO_3^- within treatments.

Treatment	Equation	R^2	p. value
Straw	y = -13.632 * exp1.02x	R² = 0.9777	**< .05**
Woodchip	y = -1.9053x + 183.46	R² = 0.0355	.762
Silage	y = 15.213x + 115.31	R² = 0.7198	.069
Hay	y = 21.947x - 1.6256	R² = 0.9697	**< .01**
Sheep	y = 22.4x + 45.484	R² = 0.8572	**< .05**
Cattle	y = 14.761x + 68.202	R² = 0.9008	**< .05**

Figures 3.75, 3.76, 3.77, show that NO_3^- concentrations increased significantly during composting in all treatments except woodchip and silage. There was no evidence of any trend over time in the woodchip NO_3^- profile, but there is an overall pattern of increase in the silage. Table 3.46 shows the rate at which NO_3^- levels increased over time in straw, hay and both livestock treatments, was significantly ($p<0.05$) correlated to the values predicted by the respective regression models.

Ammonium





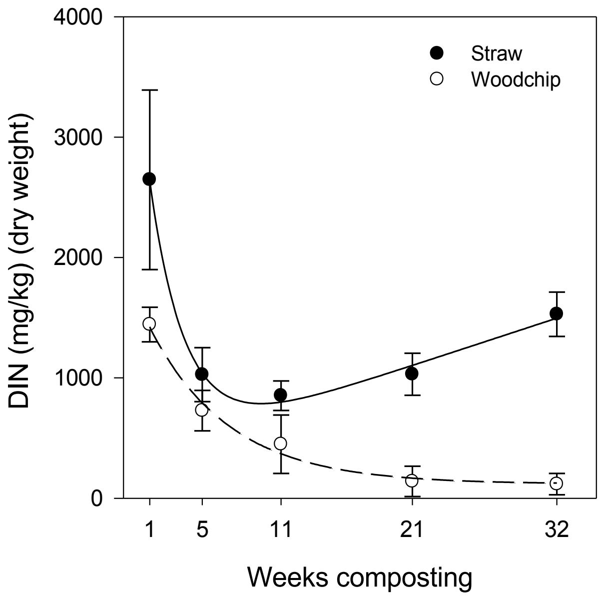
Figures 3.78 (bedding) 3.79 (livestock) *and* ***3.80 (feed):*** *show the relationship between NH_4^+ and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. All treatments were analysed using an exponential decay curve (3 parameters) f = y0+a*exp(-b*x). Values represent mean ±1 se.*

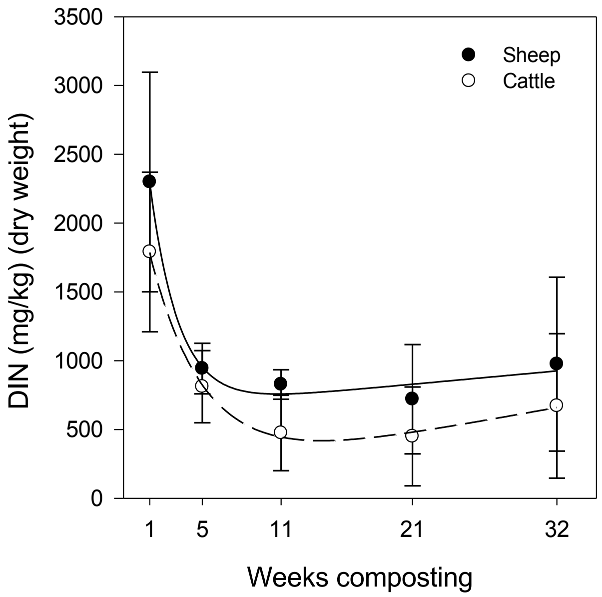
Table 3.47: NH_4^+ regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in NH_4^+ within treatments.

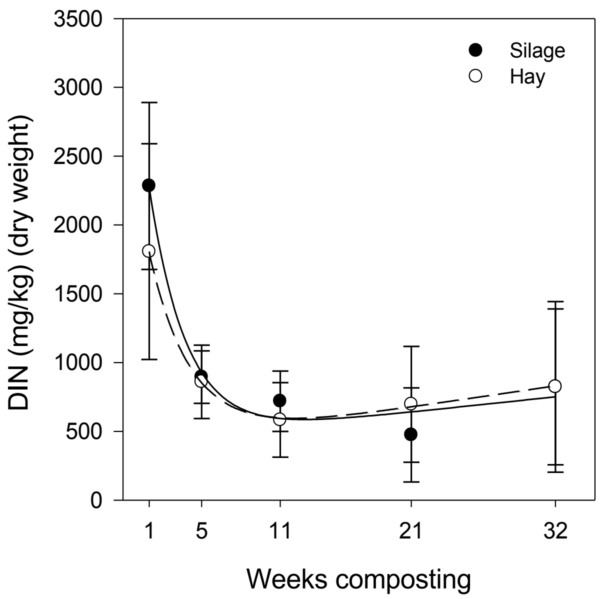
Treatment	Equation	R^2	p. value
Straw	y = 3343.8 * exp-0.30x	$R^2 = 0.9953$	**< .01**
Woodchip	y = 1867.0 * exp-0.28x	$R^2 = 0.9996$	**< .001**
Silage	y = 3053.6 * exp-0.34x	$R^2 = 0.9998$	**< .001**
Hay	y = 2177.9 * exp-0.23x	$R^2 = 0.9942$	**< .01**
Sheep	y = 2891.0 * exp-0.28x	$R^2 = 0.9998$	**< .001**
Cattle	y = 2325.5 * exp-0.31x	$R^2 = 0.9884$	**< .01**

Figures 3.78, 3.79, and 3.80, show NH_4^+ concentrations decreased rapidly during composting in all treatments as nitrification occurred up to week 11, which thereafter continued at a much lower rate, fitting the exponential decay regression curves and resulting in significant correlations in all treatments. Table 3.47 shows the rate at which NH_4^+ levels decreased over time in all treatments was significantly ($p<0.01$) correlated to the predicted values in the respective decay curve regression models.

DIN







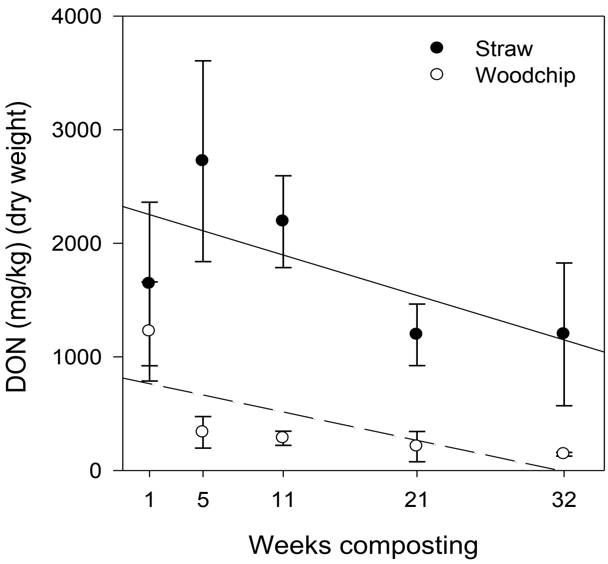
Figures 3.81 (bedding) 3.82 (livestock) *and* ***3.83 (feed):*** *show the relationship between DIN and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. An exponential decay / linear combination curve f = y0+a*exp(-b*x)+c*x was used to analyse all the treatments except Woodchip (Fig 3.75) which was analysed using an exponential decay curve (3 parameters) f = y0+a*exp(-b*x). Values represent mean ±1 se.*

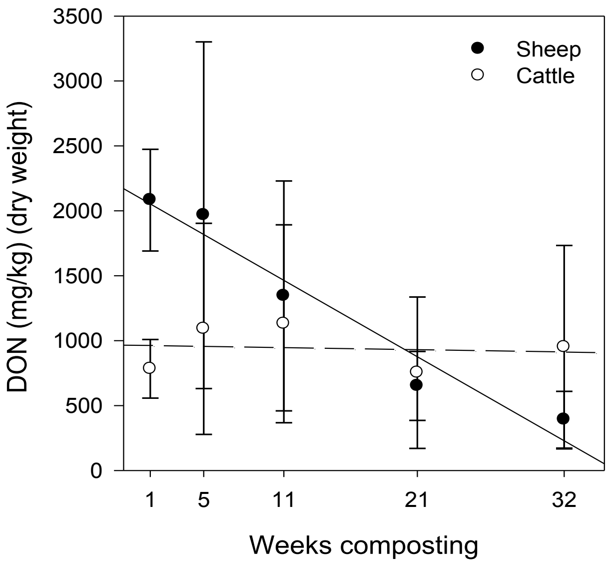
Table 3.48: DIN regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in DIN within treatments.

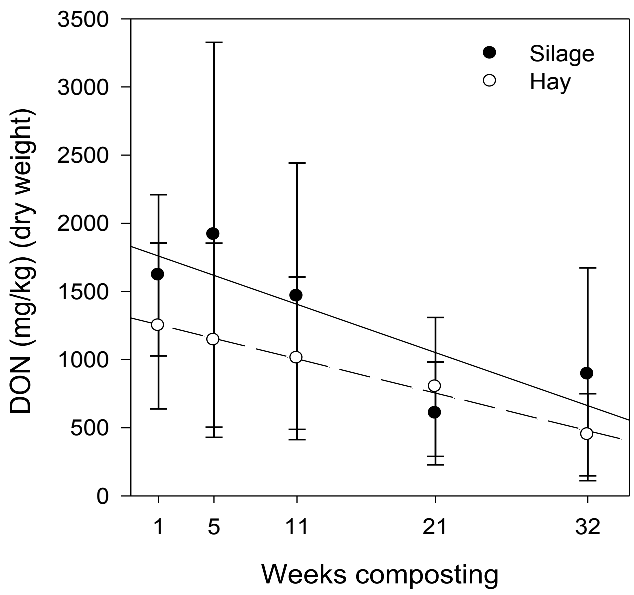
Treatment	Equation	R^2	p. value
Straw	y = 3775.7 * exp-0.37x + 35.8x	R^2 = 0.9823	. 085
Woodchip	y = 1659. 3 * exp-0.17x	R^2 = 0.9801	**< .05**
Silage	y = 3044.1 * exp-0.35x + 10.1x	R^2 = 0.9015	.199
Hay	y = 2310.9 * exp-0.31x + 14.1x	R^2 = 0.9976	**< .05**
Sheep	y = 3238. 8 * exp-0.46x + 8.81x	R^2 = 0.9543	.136
Cattle	y = 2223.0 * exp-0.24x + 17.4x	R^2 = 0.9926	.055

Concentrations of DIN in all treatments (Figures 3.81, 3.82, and 3.83) are strongly influenced by decreases in NH_4^+ during the first half of the composting period (weeks 0 – 11), after which, concentrations remained low due to the relatively smaller increases in NO_3^-. This pattern is indicative of the low level of nitrification in the woodchip composts, which is also evident in both the livestock and feed type results, although the effect on these treatments was mitigated by the inclusion of an equal number of straw bedding-composts (see table 3.12). Therefore, DIN profiles in all treatments except woodchip, were most accurately analysed using an exponential decay / linear combination curve, whereas the woodchip data was analysed with a (3 parameter) exponential decay curve. Table 3.48 shows the rate at which DIN levels decreased over time in the woodchip and hay treatments was significantly ($p<0.05$) correlated to the predicted values in the respective decay curve regression models.

DON







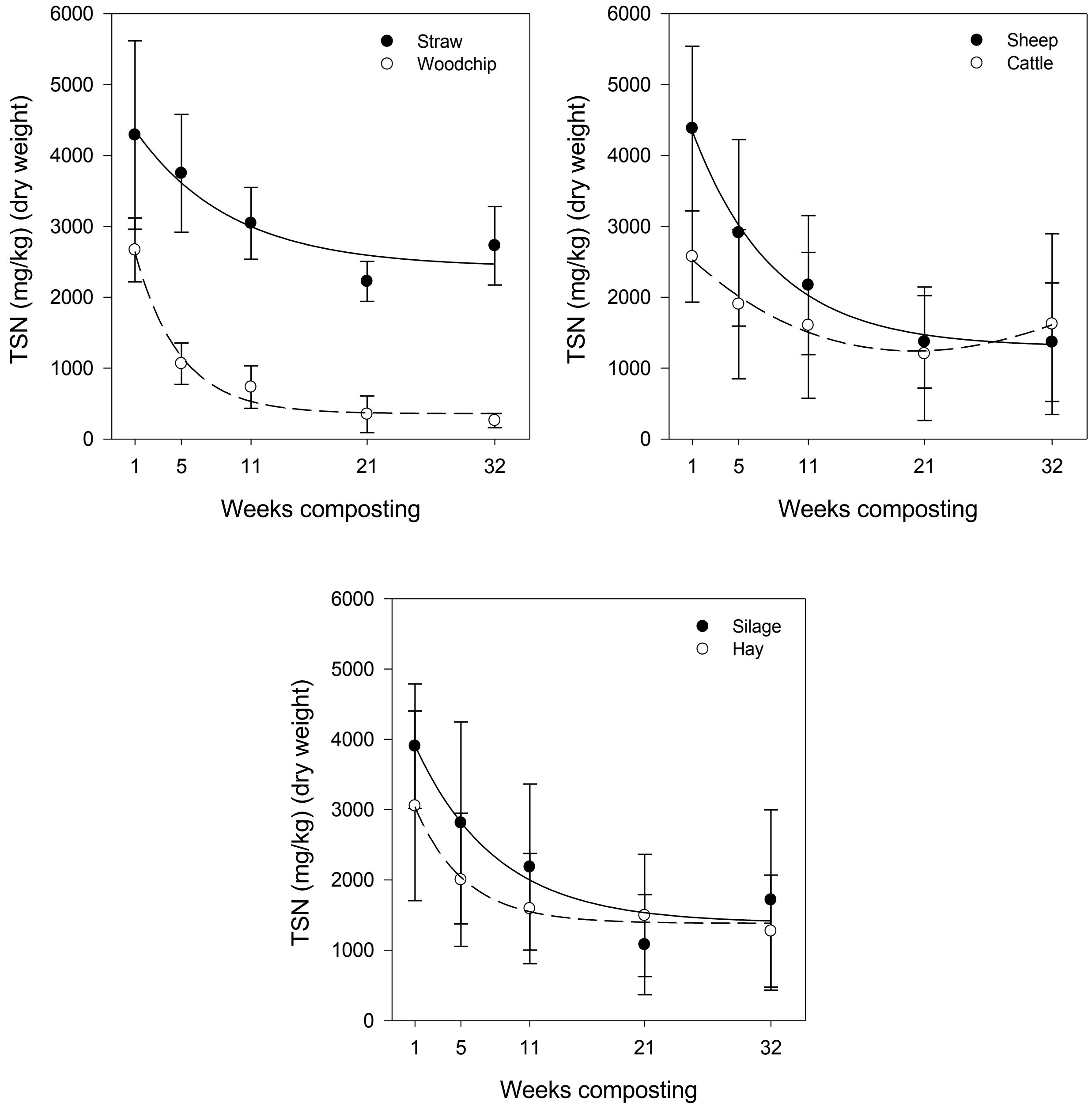
***Figures 3.84 (bedding) 3.85 (livestock)** and **3.86 (feed):** show the relationship between DON and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. Values represent mean ±1 se.*

Table 3.49: DON regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in DON within treatments.

Treatment	**Equation**	R^2	**p. value**
Straw	y = -35.589x + 2287.7	$R^2 = 0.4558$	.211
Woodchip	y = -24.893x + 787.84	$R^2 = 0.4954$	.185
Silage	y = -35.41x + 1795.2	$R^2 = 0.6851$	.084
Hay	y = -25.072x + 1280.4	$R^2 = 0.9921$	**< .001**
Sheep	y = -58.868x + 2111.4	$R^2 = 0.9503$	**< .01**
Cattle	y = -1.6141x + 964.15	$R^2 = 0.0139$	.850

Figures 3.84, 3.85, and 3.86; DON concentrations showed a general trend to decrease in all treatments during composting, but the pattern was more variable than for DIN (especially for cattle composts). In sheep, and especially hay, composts the linear decrease in DON was clearly significant, with a very steep decline for sheep (Table 3.49).

TSN



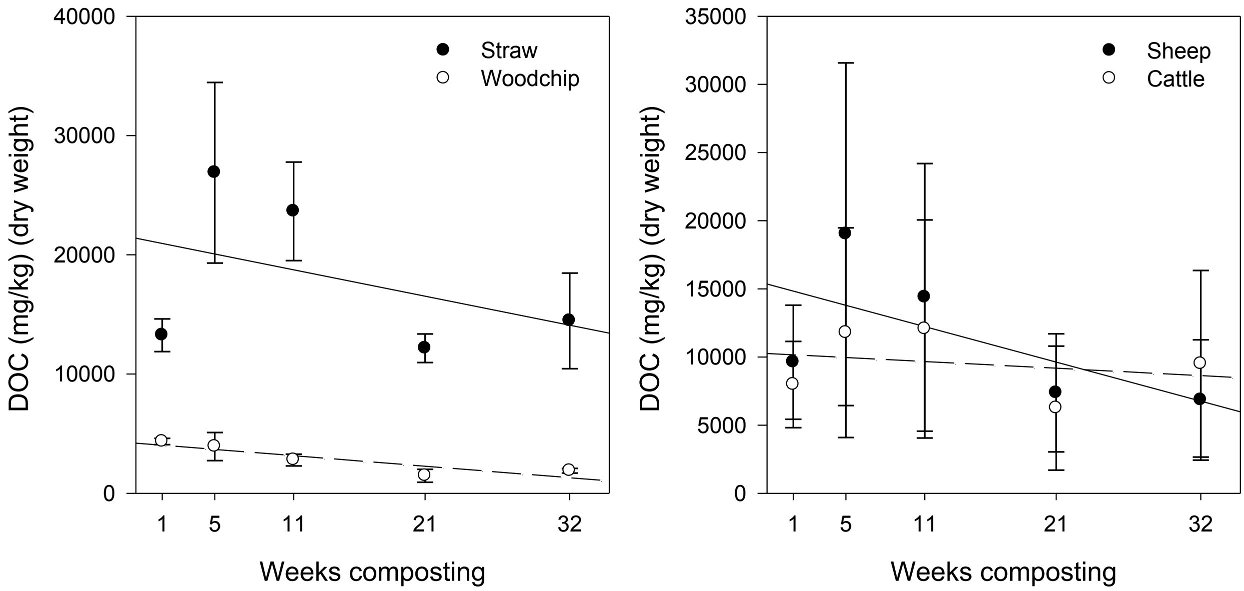
***Figures 3.87 (bedding) 3.88 (livestock)** and **3.89 (feed):** show the relationship between TSN and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. An exponential decay curve (3 parameters) f = y0+a*exp(-b*x) was used to analyse all the treatments except Cattle (Fig 3.82) which was analysed using an exponential decay / linear combination curve f = y0+a*exp(-b*x)+c*x. Values represent mean ±1 se.*

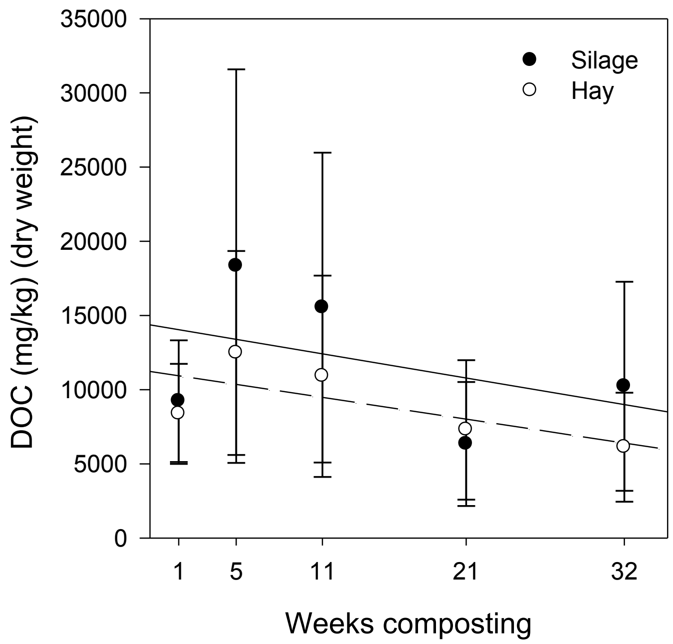
Table 3.50: TSN regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in TSN within treatments.

Treatment	Equation	R^2	p. value
Straw	$y = 4607.1 * {}_{exp}{-0.12x}$	$R^2 = 0.8290$	.085
Woodchip	$y = 3322.8 * {}_{exp}{-0.26x}$	$R^2 = 0.9670$	**< .05**
Silage	$y = 4302.8 * {}_{exp}{-0.14x}$	$R^2 = 0.8583$	.071
Hay	$y = 3476.4 * {}_{exp}{-0.23x}$	$R^2 = 0.9745$	**< .05**
Sheep	$y = 4820.3 * {}_{exp}{-0.14x}$	$R^2 = 0.9858$	**< .01**
Cattle	$y = 2684.2 * {}_{exp}{-0.03x} + 199x$	$R^2 = 0.9001$	.200

TSN is calculated as the sum of DIN and DON concentrations. Figures 3.87, 3.88, and 3.89, show that TSN, like DIN and DON concentrations, decreased in all treatments during composting. TSN in sheep composts were higher at the start of composting than cattle, due to the higher ratios of manure to bedding in sheep-straw bedding composts, but decreased at a faster rate (note: sheep beddings started composting 2 weeks before cattle beddings), resulting in both treatments containing similar concentrations at the end of composting, whereas, straw treatments contained greater amounts of TSN than wood throughout. Table 3.50 shows the rate at which TSN levels decreased over time in the woodchip, sheep and hay treatments, was significantly ($p<0.05$) correlated to the predicted values in the respective decay curve regression models.

DOC





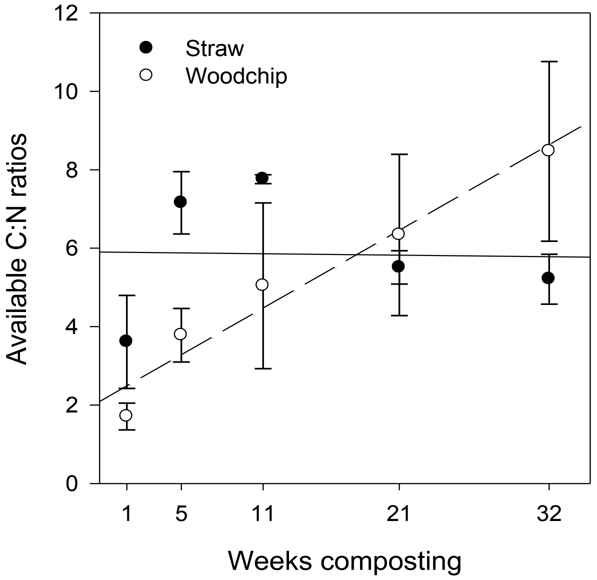
***Figures 3.90 (bedding) 3.91 (livestock)** and **3.92 (feed):** show the relationship between DOC and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. Values represent mean ±1 se.*

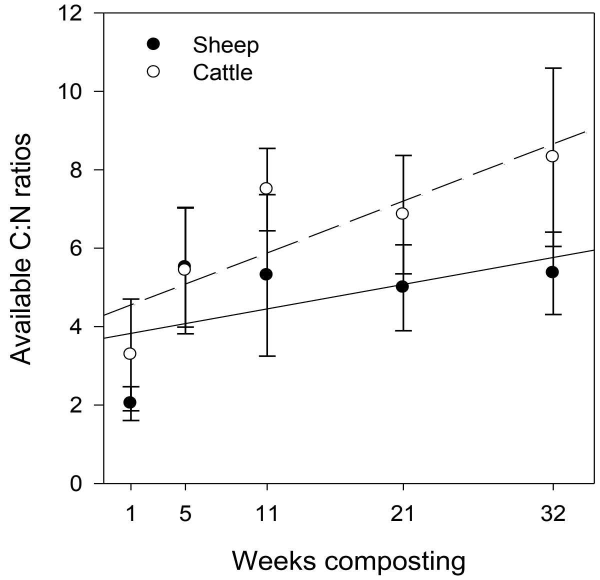
Table 3.51: DOC regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in DOC within treatments.

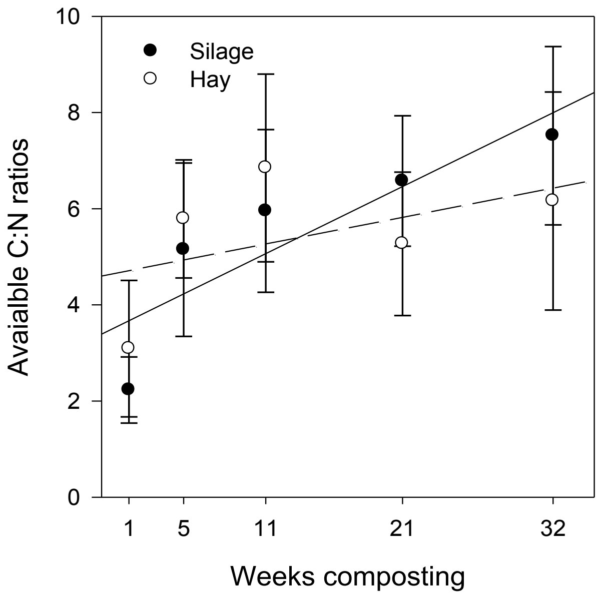
Treatment	Equation	R^2	p. value
Straw	y = -221.22x + 21176	R^2 = 0.1719	.488
Woodchip	y = -88.233x + 4119.1	R^2 = 0.7935	**< .05**
Silage	y = -163.09x + 14213	R^2 = 0.1762	.482
Hay	y = -146.36x + 11082	R^2 = 0.4963	.184
Sheep	y = -260.23x + 15089	R^2 = 0.4002	.252
Cattle	y = -49.225x + 10207	R^2 = 0.0622	.686

Figures 3.90, 3.91, and 3.92, show that DOC levels were very low in the woodchip treatment at the start, but showed very little variability between replicates, thus the small consistent decrease during composting was significant (see Table 3.51). The other treatments showed far more variability between replicates and over time.

Available C:N







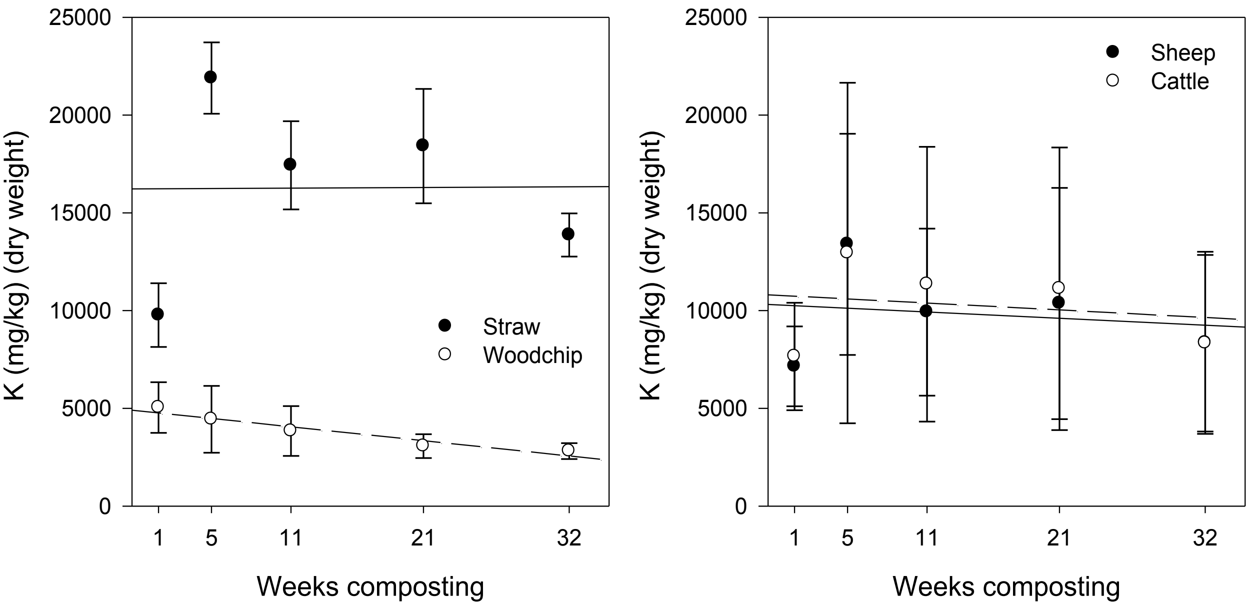
Figures 3.93 (bedding) 3.94 (livestock) *and* ***3.95 (feed):*** *show the relationship between AC:N ratio and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. Values represent mean ±1 se.*

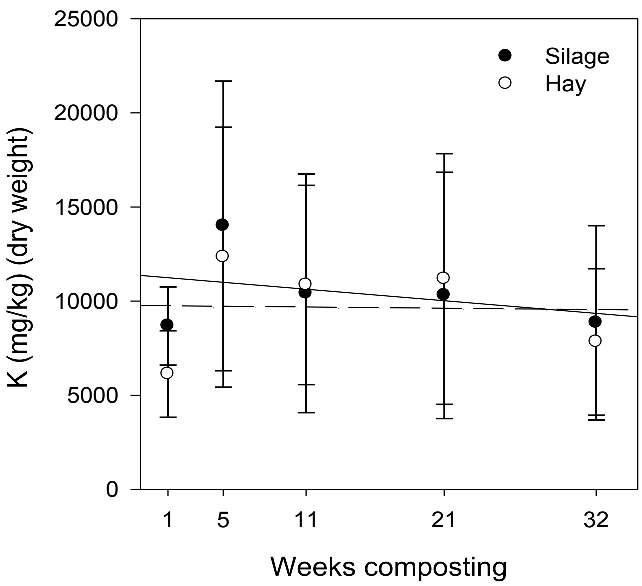
Table 3.52: Available CN regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in available CN within treatments.

Treatment	Equation	R^2	p. value
Straw	$y = -0.0036x + 5.8994$	$R^2 = 0.0007$	.965
Woodchip	$y = 0.1985x + 2.2885$	$R^2 = 0.9533$	**< .01**
Silage	$y = 0.1395x + 3.5315$	$R^2 = 0.7570$	.055
Hay	$y = 0.0553x + 4.6564$	$R^2 = 0.2370$	.406
Sheep	$y = 0.0624x + 3.7675$	$R^2 = 0.2860$	.353
Cattle	$y = 0.1325x + 4.4204$	$R^2 = 0.7074$	.074

Figures 3.93, 3.94, and 3.95 show AC:N ratios were highly variable between replicates and over time. Nonetheless, there is a striking contrast between the significant linear increase in woodchip (Table 3.52) and the non-linear pattern for straw composts (increase up to week 11 followed by a decrease). The increase in AC:N in the woodchip treatments is primarily attributable to the decrease in DOC (Figure 3.90). The linear increases in AC:N in silage and cattle treatments separately were close to significant (Table 3.52).

Potassium





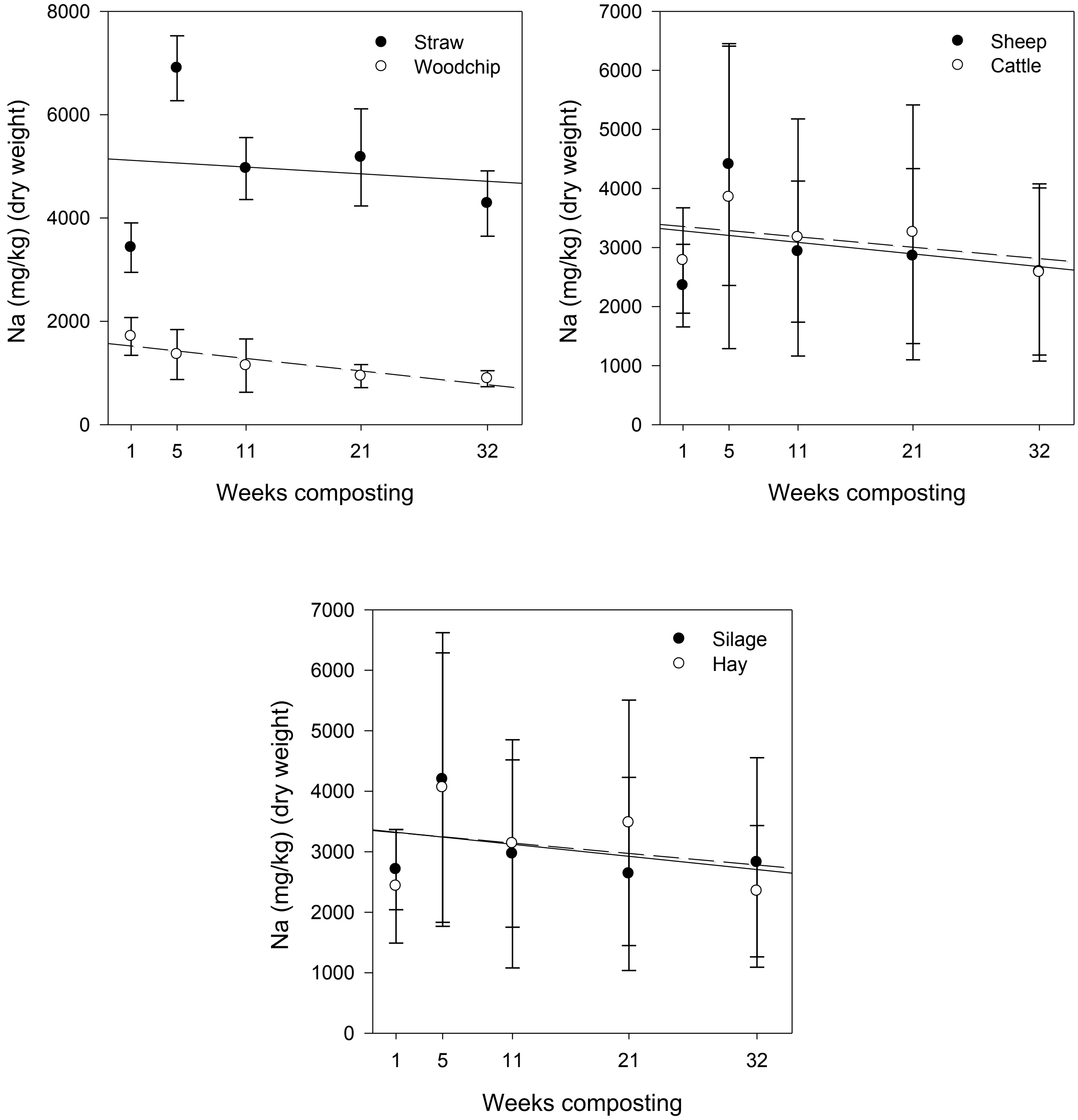
Figures 3.96 (bedding) 3.97 (livestock) *and* ***3.98 (feed):*** *show the relationship between K_2O and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. Values represent mean ±1 se.*

Table 3.53: K_2O regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in K_2O within treatments.

Treatment	Equation	R^2	p. value
Straw	y = 3.4763x + 16225	R² = 0.0001	.988
Woodchip	y = -70.951x + 4834.6	R² = 0.9242	**< .01**
Silage	y = -61.095x + 11304	R² = 0.1289	.553
Hay	y = -6.3804x + 9755.3	R² = 0.0010	.960
Sheep	y = -32.263x + 10286	R² = 0.0295	.783
Cattle	y = -35.212x + 10773	R² = 0.0399	.747

Figures 3.96, 3.97 and 3.98, show high variability in K concentrations between replicates and over time in all treatments except woodchip composts, which show a small but highly significant decrease over time (Table 3.53). Despite the high variability amongst replicates there was a striking similarity in the non-linear fluctuations in K, over time, amongst sheep, cattle, silage and hay treatments, analysed separately. It is clear that the overwhelming contrast is between the trends for straw composts (showing no trend over time) and woodchip (the only treatment to contain lower concentrations at week 32 than week 1 (Figure 3.117)). This is considered to be the result of greater leaching from the woodchip than the straw composts.

Sodium



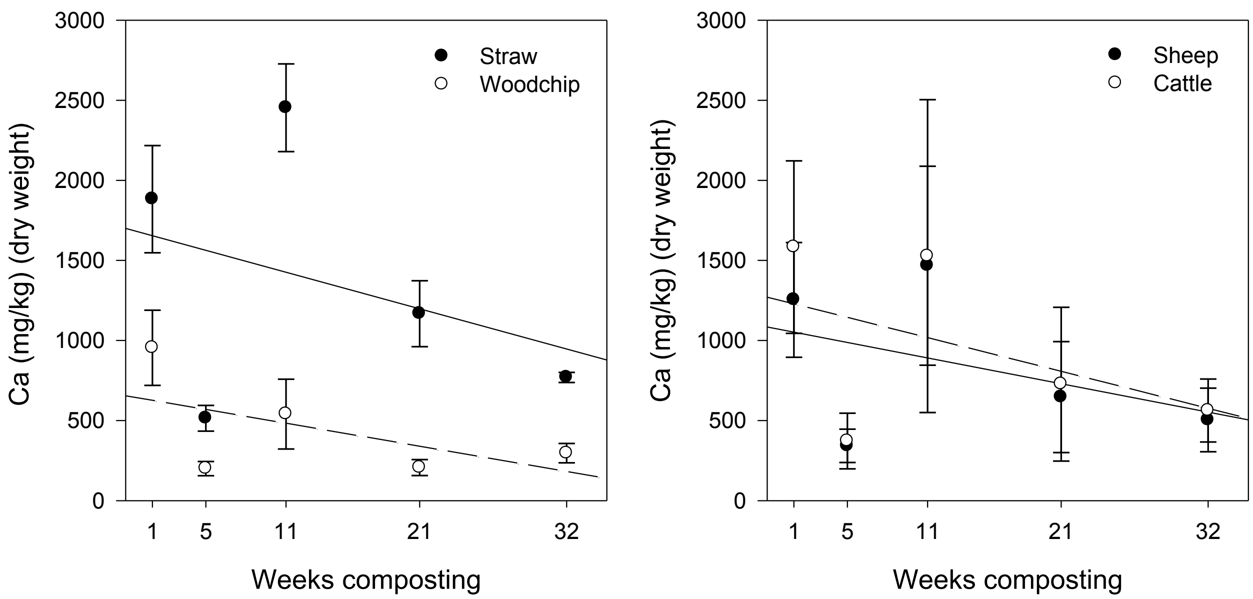
***Figures 3.99 (bedding) 3.100 (livestock)** and **3.101 (feed):** show the relationship between Na and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. Values represent mean ±1 se.*

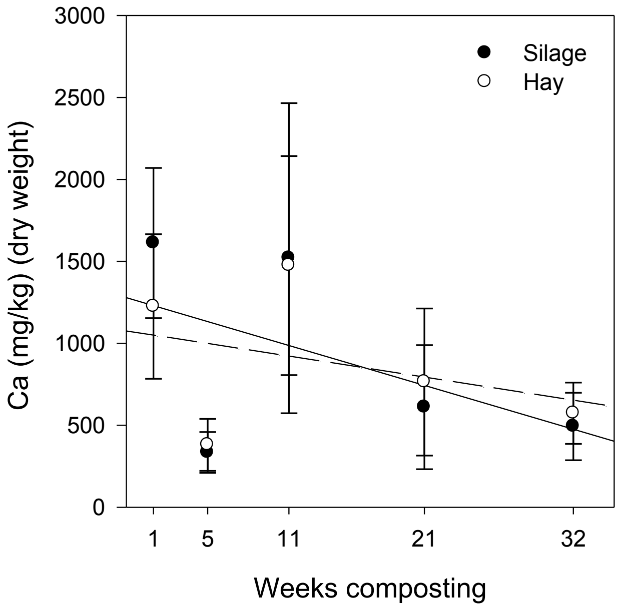
Table 3.54: Na regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in Na within treatments.

Treatment	Equation	R^2	p. value
Straw	y = -13.049x + 5129.8	$R^2 = 0.0163$	.838
Woodchip	y = -24.104x + 1545.2	$R^2 = 0.8176$	**< .05**
Silage	y = -19.864x + 3342.4	$R^2 = 0.1503$	.519
Hay	y = -17.29x + 3332.7	$R^2 = 0.0908$	.622
Sheep	y = -19.562x + 3302.1	$R^2 = 0.0939$	.616
Cattle	y = -17.592x + 3373	$R^2 = 0.2028$	.447

Figures 3.99, 3.100 and 3.101 and Table 3.54 show a strikingly similar set of results for Na concentrations as for K. Again, woodchip (small significant decrease over time) versus straw (no trend over time) was the dominant contrast. Figure 3.118 shows that Na was leached to such an extent from the woodchip composts during composting ($p<0.05$), that the losses dominated results in the cattle and hay treatments also.

Calcium





***Figures 3.102 (bedding) 3.103 (livestock)** and **3.104 (feed):** show the relationship between Ca and composting time in bedding, livestock and feed types. Solid regression lines relate to black dot treatment icons; dashed regression lines, to white dot treatment icons. Values represent mean ±1 se.*

Table 3.55: Ca regression equations and corresponding R^2 values per treatment; ($p<0.05$) shows that composting time is a significant factor in determining changes in Ca within treatments.

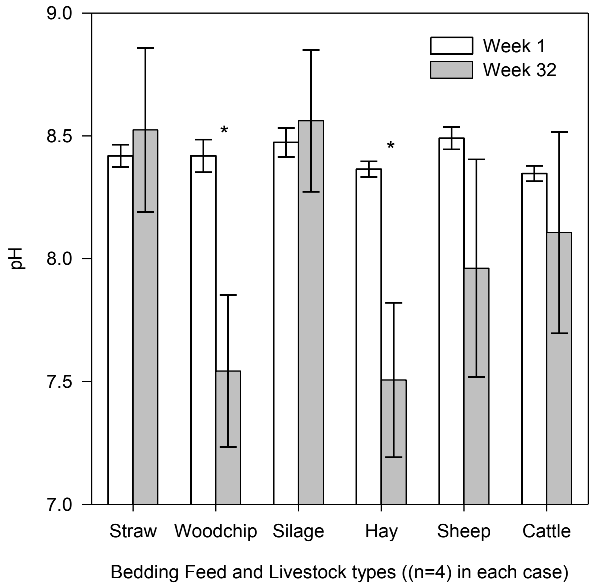
Treatment	Equation	R^2	p. value
Straw	y = -22.843x + 1677.3	$R^2 = 0.1284$	.554
Woodchip	y = -14.313x + 640.07	$R^2 = 0.3180$	.322
Silage	y = -24.334x + 1254.4	$R^2 = 0.2564$	.384
Hay	y = -12.822x + 1063	$R^2 = 0.1253$	.559
Sheep	y = -16.124x + 1068.4	$R^2 = 0.1707$	.489
Cattle	y = -21.032x + 1249	$R^2 = 0.2207$	.425

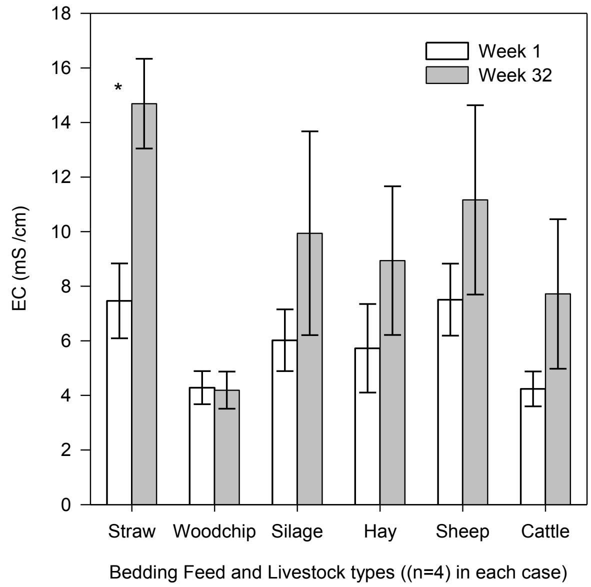
Figures 3.102, 3.103 and 3.104 show Ca concentrations were also strongly influenced by bedding material (woodchip versus straw). While there was a general pattern of decrease over time, no Ca treatment profile was significantly correlated (Table 3.55). The non-linear fluctuations over time were very similar between in sheep, cattle, silage and hay treatments, although this is attributed to rates of loss in seepage, determined predominately by the physical and labile properties of the two bedding materials). However, Figures 3.102 and 3.119 show that, unlike K and Na, a large proportion of the initial Ca was also leached from straw composts, not just from woodchip.

3.3.5.5 Chemical changes between the start and end of composting

The following graphs show change in compost nutrient concentrations between the start (Week 1) and end (Week 32) of composting at IGER. Symbols displayed above paired columns denote significant (* $p<0.05$; ** $p<0.01$ and *** $p<0.001$) differences in the tested concentrations within each treatment, between the start and end of composting; (n= #) displayed after each treatment denotes the number of compost means (each, the mean of 4 samples) included in the data.

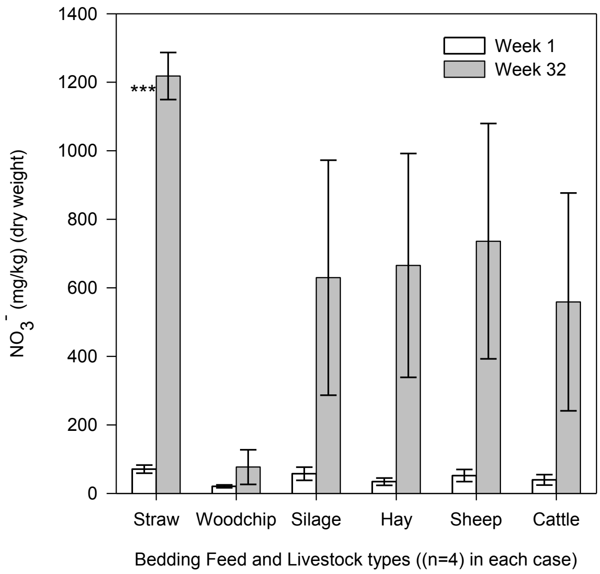
pH and EC

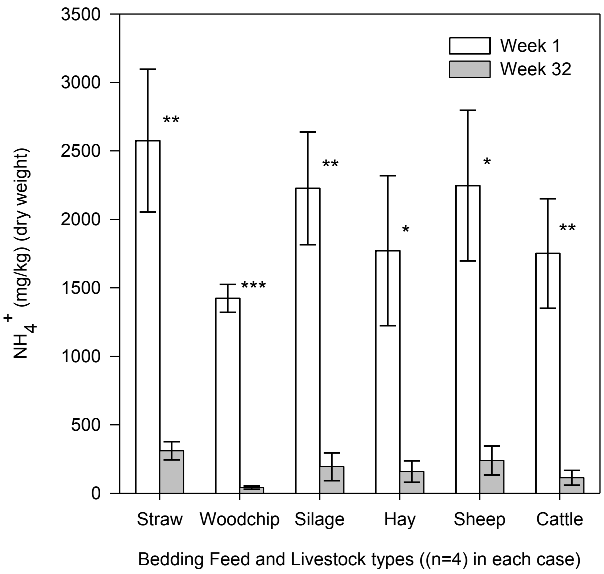




***Figures 3.105 (pH)** and **3.106 (EC):** pH and EC levels in IGER treatments at week 1 (white bars) and week 32 (grey bars). Values represent mean ±1 se. Symbols displayed above treatment columns represent (* $p<0.05$; ** $p<0.01$ and *** $p<0.001$) significant changes over time.*

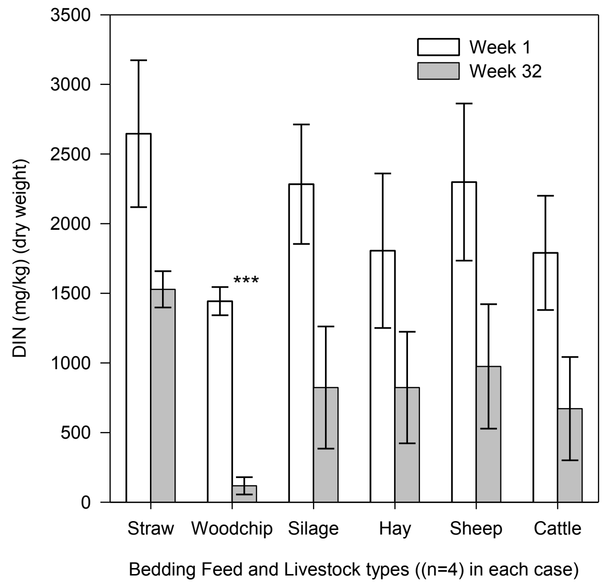
Nitrate and Ammonium

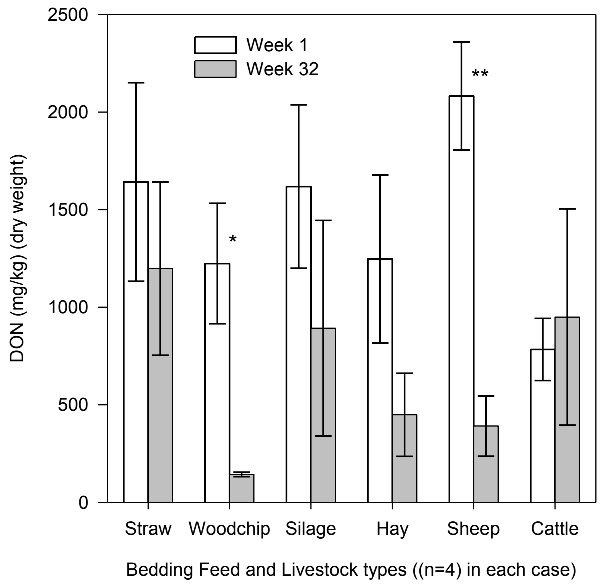




Figures 3.107 (NO_3^-) and 3.108 (NH_4^+): *Nitrate and ammonium in IGER treatments at week 1 (white bars) and week 32 (grey bars). Values represent mean ±1 se. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in concentrations over time.*

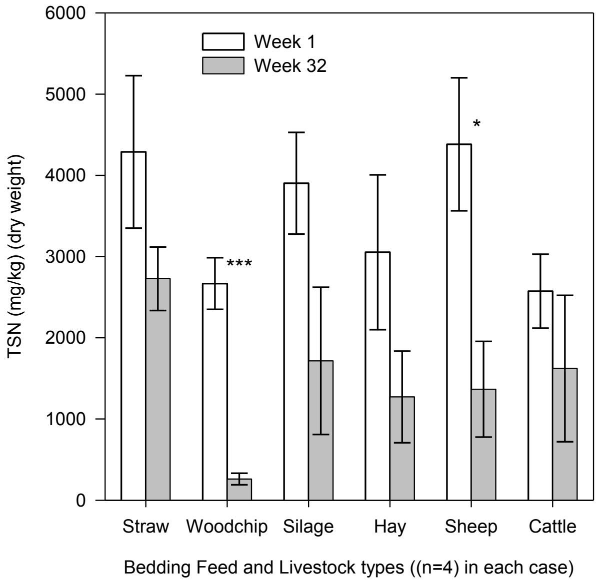
DIN and DON

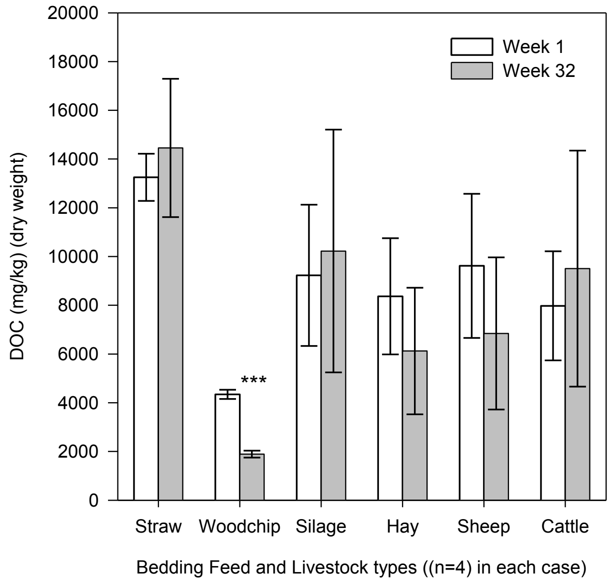




Figures 3.109 (DIN) and 3.110 (DON): *Dissolved inorganic nitrogen and dissolved organic nitrogen in IGER treatments at week 1 (white bars) and week 32 (grey bars). Values represent mean ±1 se. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in concentrations over time.*

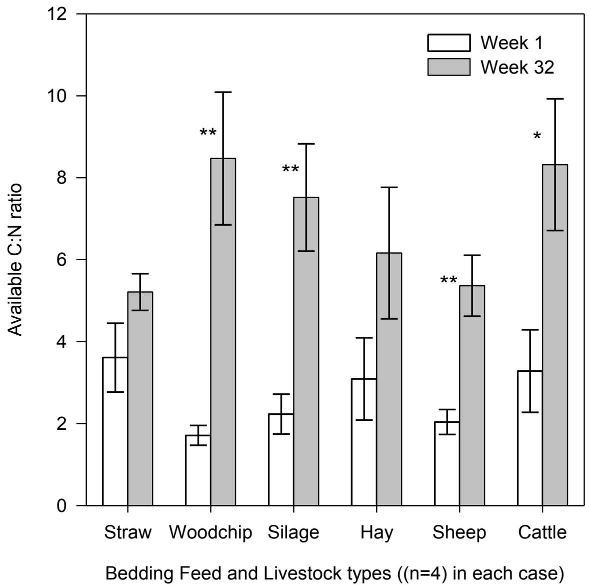
TSN and DOC

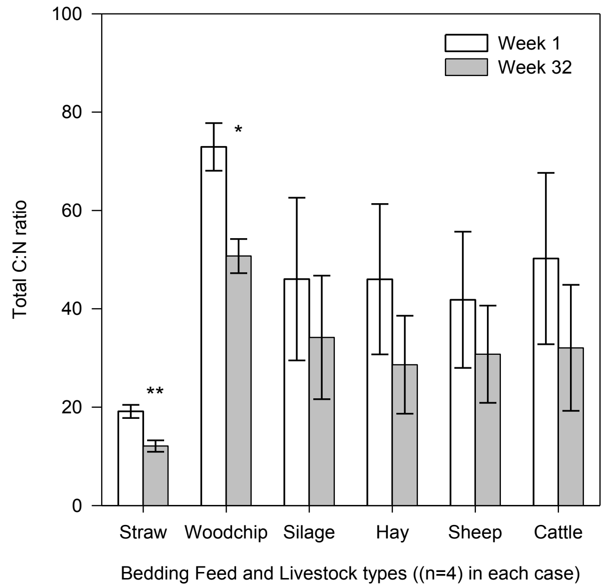




***Figures 3.111 (TSN)** and **3.112 (DOC):** Total soluble nitrogen and dissolved organic carbon in IGER treatments at week 1 (white bars) and week 32 (grey bars). Values represent mean ±1 se. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in concentrations over time.*

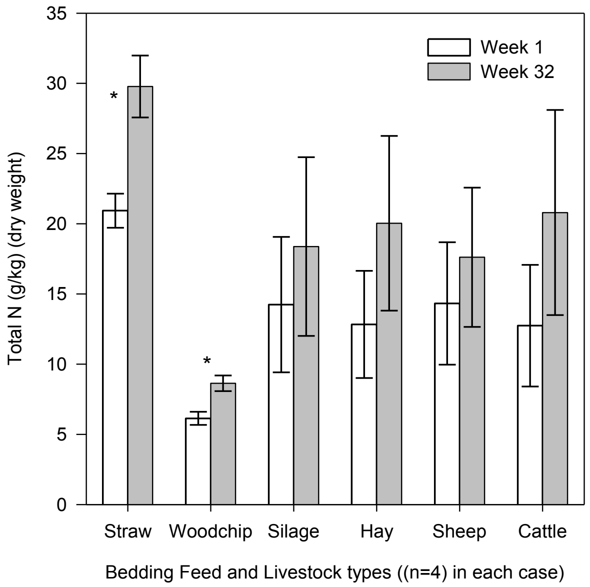
Available C:N and Total C:N

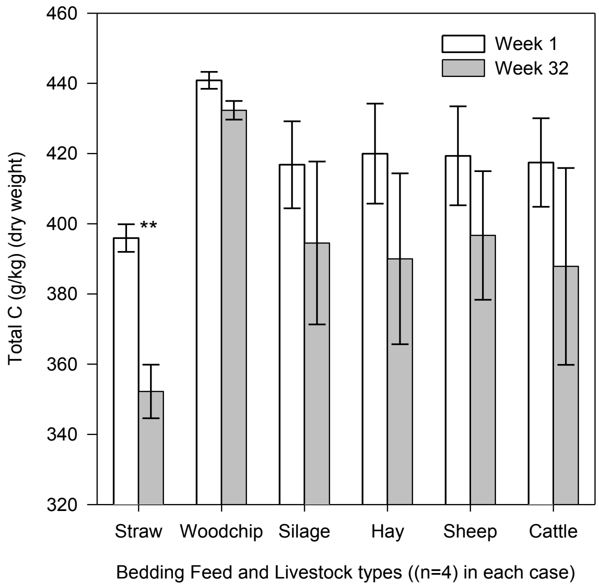




***Figures 3.113 (AC:N)** and **3.114 (TC:N):** Available CN and total CN ratios in IGER treatments at week 1 (white bars) and week 32 (grey bars). Values represent mean ±1 se. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in concentrations over time.*

TN and TC





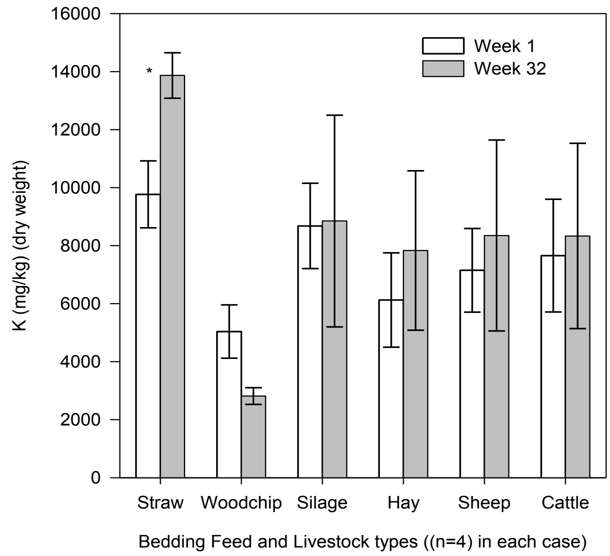
***Figures 3.115 (TN)** and **3.116 (TC):** Total nitrogen and total carbon in IGER treatments at week 1 (white bars) and week 32 (grey bars). Values represent mean ±1 se. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in concentrations over time.*

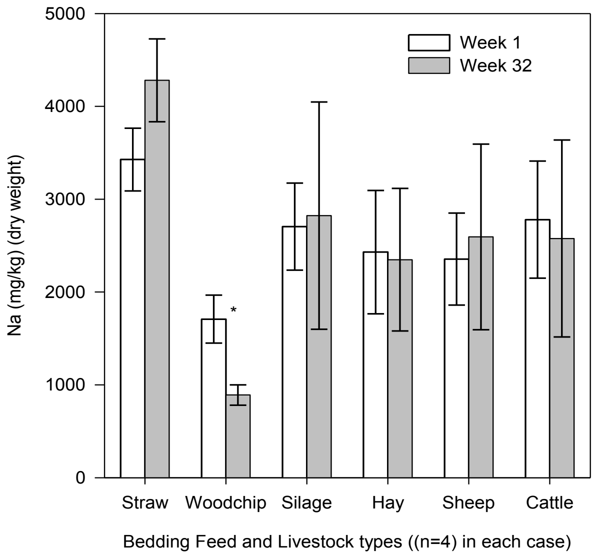
Table 3.56: Percentage of total N as available N (AN) (left), and percentage of total C as available C (AC) (right), at the start and end of the IGER composting trial.

IGER	% of Total N as AN	
Treatments (n=4)	Week 1	Week 32
Straw	20.1	9.2
Wood	43.9	3.0
Silage	36.7	6.9
Hay	27.2	5.3
Sheep	35.7	6.5
Cattle	28.2	5.7

IGER	% of Total C as AC	
Treatments (n=4)	Week 1	Week 32
Straw	3.4	4.1
Wood	1.0	0.4
Silage	2.3	2.9
Hay	2.1	1.7
Sheep	2.4	1.8
Cattle	2.0	2.7

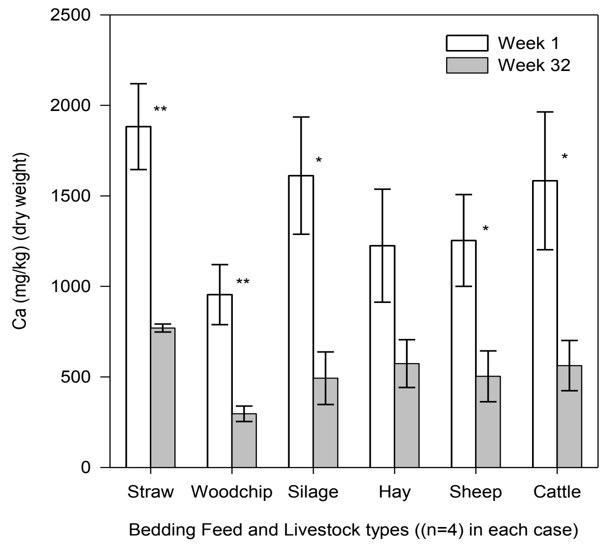
Potassium and Sodium

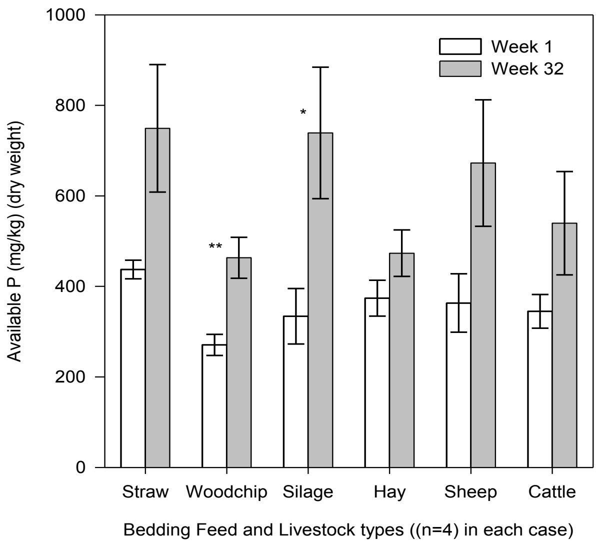




Figures 3.117 ($K_2 0$) and 3.118 (Na): *Potassium and sodium in IGER treatments at week 1 (white bars) and week 32 (grey bars). Values represent mean ±1 se. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in concentrations over time.*

Calcium and Available (soluble) P





Figures 3.119 (Ca) and 3.120 (P_2O_5): *Calcium and soluble P in IGER treatments at week 1 (white bars) and week 32 (grey bars). Values represent mean ±1 se. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in concentrations over time.*

There was a significant drop in pH in both woodchip and hay composts ($p<0.05$) (Figure 3.105), although all treatments remained within a pH range of 7 to 9 over the composting period. Concentrations of soluble salts were highly contrasting between bedding types: EC readings in straw composts were significantly higher after composting than at the start, whereas EC readings in woodchip remained almost unchanged throughout (Figure 3.106). NH_4^+ decreased significantly in all treatment types during composting (Figure 3.108) but notably, NO_3^- only increased significantly in straw (Figure 3.107, see section 3.4 for further discussion). DIN ($p<0.001$), DON ($p<0.05$), TSN ($p<0.001$) and DOC ($p<0.001$) all decreased significantly in woodchip during composting (Figures 3.109-3.112). The significant drop in DOC is of particular concern, as concentrations at the start of composting were already critically low for microbial growth and function. Thus, as the ADAS data shows, AC:N ratios remained below 10:1 in woodchip treatments throughout the composting period (Figure 3.113); so decomposition would appear to have been inhibited as much by a lack of AC as by the lack of AN. Although, increases in TN were significant ($p <0.05$) at IGER (Figure 3.115), they were less so than at ADAS ($p <0.001$) (Figure 3.58). TN levels in IGER's woodchip composts also remained very low in comparison with straw-based treatments, reflecting the high TC:N (Figure 3.114) and TC (Figure 3.116) concentrations still present at the end of composting. The percentage of TN as AN in IGER's woodchip treatment was higher at the start and end of composting (Table 3.56) than at ADAS (Table 3.37). This is possibly due to manure not being removed at IGER. Nevertheless, the proportion of TN as AN at the end of composting is still low compared with the straw treatment. At both sites, the low percentages of TN as AN are likely to have been due to immobilization. Concentrations of K and Na increased in the straw treatment during composting, but decreased in woodchip (Figures 3.117 and 3.118). This contrast is considered to be the result of greater mass loss in the more labile straw compost, although both bedding materials will have lost nutrients via seepage. Ca concentrations decreased significantly in all treatments except hay during composting at IGER (Figure 3.119). Most notable are the decreases in both woodchip and straw treatments ($p <0.001$), demonstrating the levels of Ca lost (considered to be via seepage and immobilization) were highly significant in both bedding types, not just woodchip, as was the case for K and Na). Soluble P concentrations increased in all treatments during composting, significantly in woodchip ($p <0.01$) and silage ($p <0.05$) (Figure 3.120). These increases may, in part, be due to compost mass loss, but the reason for a significant increase in the woodchip and a non-significant increase in the straw compost remains unclear (Larney 2008(a)).

3.3.5.6 Chemical characterisation of treatments at the end of composting

Table 3.57: Nutrient concentrations at week 32 in the bedding, feed and livestock treatments in the IGER experiment, including ±1 se. Symbols displayed between paired treatment types represent (* p<0.05; ** p<0.01 and *** p<0.001) differences in variable concentrations.

IGER	Straw			Wood		Silage			Hay		Sheep			Cattle	
Week 32	(n=4)	se		(n=4)	se	(n=4)	se		(n=4)	se	(n=4)	se		(n=4)	se
pH	8.52	± 0.33	**	7.54	± 0.31	8.56	± 0.29	**	7.51	± 0.31	7.96	± 0.44		8.11	± 0.41
EC mS/cm	14.7	± 1.64	**	4.19	± 0.68	9.94	± 3.73		8.94	± 2.72	11.2	± 3.47	*	7.72	± 2.74
NO_3^- mg/kg	1218	± 68.8	***	76.9	± 50.6	630	± 343		666	± 327	736	± 344	*	559	± 318
NH_4^+ mg/kg	311	± 66.4	**	40.8	± 12.1	193	± 102		158	± 78.5	239	± 105		113	± 54.3
DIN mg/kg	1529	± 130	***	118	± 62.4	823	± 439		823	± 400	975	± 447	*	672	± 371
DON mg/kg	1198	± 444		143	± 11.3	892	± 552		449	± 213	391	± 154		950	± 554
TSN mg/kg	2727	± 392	**	261	± 70.5	1715	± 906		1272	± 563	1366	± 590		1622	± 902
DOC mg/kg	14456	± 2836	**	1895	± 142	10225	± 4982		6126	± 2598	6845	± 3122		9506	± 4841
AC:N	5.21	± 0.45		8.47	± 1.62	7.52	± 1.31		6.16	± 1.60	5.36	± 0.74		8.32	± 1.61
K mg/kg	13866	± 781	***	2815	± 288	8849	± 3649		7832	± 2749	8348	± 3293		8333	± 3194
Na mg/kg	4280	± 447	**	891	± 109	2823	± 1224		2348	± 768	2594	± 1000		2577	± 1061
Ca mg/kg	770	± 22.0	***	296	± 43.0	493	± 145		573	± 132	504	± 140		563	± 139
AP mg/kg	749	± 141		463	± 45.1	739	± 145		473	± 51.3	673	± 140		540	± 114
TP mg/kg	5130	± 356	**	1734	± 117	3554	± 1109		3310	± 908	3237	± 785		3627	± 1192
TN g/kg	29.8	± 2.20	**	8.64	± 0.56	18.4	± 6.37		20.0	± 6.22	17.6	± 4.96		20.8	± 7.30
TC g/kg	352	± 7.64	**	432	± 2.65	395	± 23.2		390	± 24.3	397	± 18.3		388	± 28.0
TC:N	12.1	± 1.18	***	50.7	± 3.46	34.2	± 12.6		28.6	± 10.0	30.8	± 9.88		32.1	± 12.8
Cu mg/kg	18.6	± 2.55	**	10.0	± 0.59	15.7	± 3.49		12.9	± 2.38	12.0	± 2.04		16.5	± 3.41
Zn mg/kg	117	± 13.4	*	88.1	± 8.54	100	± 15.1		106	± 12.7	120	± 12.6	*	85.1	± 5.43

The data in Table 3.57 shows all nutrient concentrations are significantly higher in the straw than the woodchip treatment after composting, except for DON ($p = 0.062$) and soluble P ($p = 0.051$). The significance of the differences in TC:N ratio (12:1 in straw and 51:1 in woodchip) is perhaps the most fundamental, because of the effect ratios < 40:1 have on microbial function (Bernal 2009). Furthermore, the results illustrate the dominant influence of bedding type, in contrast to feed and livestock types. Where only pH differed significantly ($p < 0.01$) between silage and hay and EC, NO_3^-, DIN and Zn levels were significantly ($p < 0.05$) higher in sheep than cattle composts.

3.3.6 Nutrient balances (N Budget) in ADAS and IGER trials

Due to limitations in the housing and composting trial protocols, empirical data are supported by estimates, derived from (IOTA - online), which are highlighted with italics. The different livestock demographics, feed types and protocols deployed in each of the four livestock trials increased the complexity of these analyses, so data sources and calculations are described where necessary. Attention is also drawn to data presentation in the summary tables (section 3.3.6.6); these are aggregated into the four bedding-livestock treatments per site, determined as total N mass, divided by the total number of livestock. But in order to fully convey the results, data presented in sections 3.3.6.2 - 3.3.6.5 are specific to each treatment pen; see Tables 3.9 – 3.12 in section 3.2.5 for details of treatment groups.

3.3.6.1 Summary of experimental designs at ADAS and IGER

3.3.6.1.1 ADAS

ADAS Livestock	Sheep	Cattle
Demographics	Twin bearing ewes	12 month old bullocks
Total livestock number	120	32
Livestock per treatment	30	8
Mean live weights at start (kg hd^{-1})	52.3 (36.5 - 71)	399 (394 - 402)
Mean live weights at end (kg hd^{-1})	na	402 (393 - 414)
Housing period dates ~ 8 weeks	25/1/06 - 23/3/06	25/1/06 - 23/3/06
Area allowance m^2 hd^{-1}	1.03	5.70

ADAS Feed	Concentrates	Silage
% DM	90 (Dumont, 2012)	23.5 ± 3
Sheep mean DMi kg hd^{-1} d^{-1}	0.50	0.56
Cattle mean DMi kg hd^{-1} d^{-1}	2.00	4.73
Feeding rates	ad libitum	ad libitum

ADAS Bedding	Straw	Woodchip
Sheep total DM kg hd^{-1}	19.9	76.7
Cattle total DM kg hd^{-1}	168	336
% DM	10.8	66, 47 and 45
C:N ratios	96.0	407, 590 and 437

3.3.6.1.2 IGER

IGER Livestock	Sheep	Cattle
Demographics	12 month old ewe lambs	15 month old dairy heifers
Total livestock number	64	24
Livestock per treatment	16	6
Mean live weights at start (kg hd^{-1})	53.9 (53.8 - 54.0)	335 (328 - 339)
Mean live weights at end (kg hd^{-1})	52.4 (47.7 - 56.0)	374 (355 - 392)
Housing period dates ~ 8 weeks	20/1/06 - 17/3/06	3/2/06 - 31/3/06
Area allowance m^2 hd^{-1}	2.42	6.45

IGER Feed	Hay	Silage
% DM	82.7	29.6
Sheep DMi kg hd^{-1} d^{-1}	0.74	0.90
Cattle DMi kg hd^{-1} d^{-1}	6.13	7.03
Feeding rates + frequency	ad libitum+10 % d^{-1}	ad libitum+10 % $/wk^{-3}$

IGER Bedding	Straw	Woodchip
Sheep DM kg hd^{-1}	13.5	56.9
Cattle DM kg hd^{-1}	272	560
% DM	13.5	50.7
C:N ratio	81.0	344

3.3.6.2 Bedding N content

Data in Table 3.58 is determined by multiplying raw bedding kg hd^{-1} DM, shown in Tables 3.3 (ADAS) and 3.4 (IGER) by the raw bedding N content (g kg^{-1}) shown in Tables 3.20 (ADAS) and 3.41 (IGER).

Table 3.58: Dry matter (DM) bedding N content hd^{-1} $treatment^{-1}$ at ADAS and IGER

ADAS	Bedding type	g N hd^{-1}	IGER	Bedding type	g N hd^{-1}
S34	Wood	92.6	SSS	Straw	94.0
S53	Wood	60.4	SSC	Wood	91.6
S55	Wood	85.3	SHS	Straw	53.3
SS	Straw	89.4	SHC	Wood	68.9
C34	Wood	424	CSS	Straw	1508
C53	Wood	266	CSC	Wood	930
C55	Wood	356	CHS	Straw	1462
CS	Straw	756	CHC	Wood	651

3.3.6.3 Forage dry matter intakes (DMi) and estimated N content

DMi g hd^{-1} d^{-1} is determined as: Total DMi pen^{-1} shown in Tables 3.5 (ADAS) and Table 3.6 (IGER) / 56 (housing period (days)) divided by livestock $treatment^{-1}$ (ADAS sheep n=30 and cattle n=8; IGER sheep n=16 and cattle n=6) * 1000 (to convert kg to g). The (IOTA, online) estimated percentages of N in fresh silage and fresh hay are: silage 0.69 % N and hay 1.49 % N. Note that these % N figures are on a fresh weight basis, and therefore % N increases the lower the forage DM content. On a dry weight basis: ADAS sheep silage 20.4 % DM content = 3.38 % N (DM); ADAS cattle silage 26.7 % DM content = 2.58 % N (DM). At IGER (unlike ADAS), the same silage and hay was fed to both sheep and cattle, so feed specific DM contents were the same, but livestock either received silage 29.6 % DM = 2.33 % N (DM) or hay 82.7 % DM = 1.8 % N (DM). To avoid increased distortion in the estimated % N in hay and silage at IGER (Table 3.61) - and, more widely, between forage, livestock and manure – all estimates were determined using a single source (IOTA) but were cross-referenced with empirical publications to ensure the estimates were representative.

ADAS sheep and cattle were both fed silage, supplemented daily with concentrates. Silage dry matter intakes (DMi) and estimated N contents (IOTA) are detailed in Table 3.59 and concentrate intakes and N contents in Table 3.60. The N content in cattle concentrates was determined, assuming 16% (DM) crude protein (Dumont 2012).

Table 3.59: ADAS silage dry matter intakes (DMi) and *estimated* N content hd^{-1} d^{-1}

ADAS	DMi g hd^{-1} d^{-1}	N g hd^{-1} d^{-1}
S34	537	*18.2*
S53	560	*18.9*
S55	560	*18.9*
SS	563	*19.1*
C34	5100	*132*
C53	4500	*116*
C55	4800	*124*
CS	4500	*116*

Table 3.60: ADAS concentrate intakes and (DM) *estimated* N content hd^{-1} d^{-1}

ADAS	Concentrates	g hd^{-1} d^{-1}	N g hd^{-1} d^{-1}
Sheep	(18 % CP)	500	*14.4*
Cattle	(16 % CP)	2000	*51.2*

Table 3.61: IGER dry matter forage intakes (DMi) and *estimated* N content hd^{-1} d^{-1}

IGER	DMi g hd^{-1} d^{-1}	N g hd^{-1} d^{-1}
SSS	919	*21.4*
SSC	873	*20.4*
SHS	741	*13.3*
SHC	739	*13.3*
CSS	7174	*167*
CSC	6889	*161*
CHS	6113	*110*
CHC	6151	*111*

3.3.6.4 Livestock N content

Initially, estimates of N in sheep and cattle were calculated following the methods of Garret (1959), but the resulting inputs, when combined with bedding and estimated forage data proved too high, so revised estimates were calculated using (IOTA) data. Livestock live-weights (L-W) are calculated as mean weight pen^{-1}. Sheep N content is calculated assuming 2.75 kg of L-W is fleece containing 146 g N kg^{-1} and the remaining body mass contains 20 g N kg^{-1}. Cattle N content is estimated to be 32 g N kg^{-1} (IOTA).

Table 3.62: ADAS livestock live weights (L-W) and *estimated* N content $head^{-1}$ at start and end of housing

ADAS	Start L-W kg hd^{-1}	N kg hd^{-1}	End L-W kg hd^{-1}	N kg hd^{-1}
S34 (n=30)	52.3	*1.39*	-	-
S53 (n=30)	52.4	*1.39*	-	-
S55 (n=30)	52.3	*1.39*	-	-
SS (n=30)	52.2	*1.39*	-	-
C34 (n=8)	400	*12.8*	393	*12.6*
C53 (n=8)	402	*12.9*	405	*13.0*
C55 (n=8)	402	*12.9*	414	*13.2*
CS (n=8)	394	*12.6*	396	*12.7*

NB: the ewes were in late gestation after housing so no live-weights were assessed.

Table 3.63: IGER livestock live weights (L-W) and *estimated* N content $head^{-1}$ at start and end of housing

IGER	Start L-W kg hd^{-1}	N kg hd^{-1}	End L-W kg hd^{-1}	N kg hd^{-1}
SSS (n=16)	53.8	*1.42*	56.0	*1.47*
SSC (n=16)	53.9	*1.42*	55.9	*1.46*
SHS (n=16)	54.0	*1.43*	47.7	*1.30*
SHC (n=16)	54.0	*1.43*	49.9	*1.34*
CSS (n=6)	336	*10.8*	387	*12.4*
CSC (n=6)	336	*10.8*	392	*12.5*
CHS (n=6)	328	*10.5*	355	*11.4*
CHC (n=6)	339	*10.8*	363	*11.6*

3.3.6.5 Manure and Seepage (IGER only)

Seepage was not collected at ADAS (see 'ADAS protocol anomalies' in section 3.2.1.1) and, given the sites different protocols - particularly the bedding mass head^{-1}, moisture content treatment^{-1} and removal of manure - it is not viable to estimate ADAS seepage volumes using IGER's data.

IGER collected and analysed seepage from the bedding in each of the trial's 8 bays on a weekly basis, through a single drainage point in the centre of each bay. The floors were fractionally concave, sufficient to draw liquids. As the 3-sided bays were covered with a roof, the seepage is considered to be undiluted liquid excreta, not dirty water, as is common from OWPs. In a review to establish 'standard' figures for excretal N from different livestock demographics, Smith and Frost (2000) list an average manure output for 12 - 24 month, 400 kg cattle as 26 ltrs/kg d^{-1}. This is in agreement with estimates used in the present study, derived from DEFRA's RB209 manual, that each of IGER's 15 month old heifers produced 1370 litres of liquid excrement over the 8 weeks (DEFRA, 2010), or 24.5 ltrs/kg d^{-1}, consisting of 50 % urine (100 % moisture) and 50 % dung (90 % moisture) based on estimates used by Dumont et al (2012). These figures are put into perspective by Weiss (2004). In a dedicated study using lactating Holstein cows, Weiss (2004) reported an average manure (faeces plus urine) production of 64 kg hd^{-1} d^{-1} (27 to 102 kg d^{-1}) containing 12.5 % DM content (8.2 – 15.1 %) which, on average consisted of 32 % urine, however, urine (as % of manure) ranged between 13 to >71 %. In addition, Smith and Frost (2000) quoted a standard 10 % DM content across a wide range of livestock demographics. IGER's, cattle fed silage on woodchip (CSC n=6) treatment recorded 600 litres of undiluted seepage, equating to 7.3 % of the estimated total liquid excrement volume. In contrast, seepage from the equivalent treatment fed hay (CHC n=6) was 250 litres ~ 3.04 % and only 35 ltrs was collected from each of the cattle straw bedding treatments, equating to 0.43 % of the estimated total liquid excrement volume. Table 3.64 shows total seepage volumes head^{-1} and DIN (NH_4^+, NO_2 and NO_3^-) g head^{-1} from each cattle treatment. The candidate was not involved in the collection or analysis of seepage at IGER.

Table 3.64: IGER: Seepage volumes and DIN content head^{-1} cattle treatment^{-1}.

IGER: Seepage	Volume ltrs hd^{-1}	DIN g hd^{-1}
CSS	5.83	11.4
CSC	100	318
CHS	5.83	16.2
CHC	41.7	81.9

3.3.6.6 N balances during housing and composting at ADAS and IGER

3.3.6.6.1 ADAS: Sheep treatments

ADAS: Sheep housing	**Straw Bedding**	**Woodchip Bedding**
INPUTS	g N hd^{-1} (n=30)	g N hd^{-1} (n=90)
Bedding g N hd^{-1}	89.4	79.4
Silage DMi g N hd^{-1} (a)	*1067*	*1046*
Concentrates g N hd^{-1} (b)	806	806
Livestock g N hd^{-1} (not incl.) (c)	*1391*	*1394*
INPUT g N hd^{-1}	*1963*	*1932*
OUTPUTS		
Soiled Bedding (SB) g N hd^{-1}	803	753
Livestock g N hd^{-1} (c)	*na*	*na*
OUTPUT g N hd^{-1}	*803*	*753*
N % change - Housing	***-59.1***	***-61.0***
Estimated loss pathways 1 to 4 (1 = max loss - 4 = min loss)		
Livestock uptake	2	2
Seepage NH_4^+ and NO_3^-	4	3
NH_3 emissions	1	1
N_2O, N_2 emissions	3	4

ADAS Composting	**Straw Compost**	**Woodchip Compost**
Week 2 g N hd^{-1}	803	753
Week 33 g N hd^{-1} (d)	*534*	*786*
N % change - Composting	***- 33.5***	***4.30***

Data in *italics* are estimates derived from IOTA (online)

(a) *Silage N content 3.38 % DM (Sheep silage 20.4 % DM content) – see section 3.3.6.3*

(b) Sheep concentrate N is calculated from feed label (18 % CP) DM

(c) Sheep N uptake not determined; for safety reasons the pregnant ewes were not weighted after housing

(d) *N loss from sheep composts is estimated by multiplying TN (g /kg) at week 33 by 50 % mass loss in straw composts and 35 % mass loss in woodchip composts. Mass loss estimates are derived from IGER results*

3.3.6.6.2 ADAS: Cattle treatments

ADAS: Cattle housing	**Straw Bedding**	**Woodchip Bedding**
INPUTS	g N hd^{-1} (n=8)	g N hd^{-1} (n=24)
Bedding g N hd^{-1}	756	349
Silage DMi g N hd^{-1} (a)	*6512*	*6947*
Concentrates g N hd^{-1} (b)	*2867*	*2867*
Livestock g N hd^{-1} (c)	*12598*	*12839*
INPUT g N hd^{-1}	*22734*	*23002*
OUTPUTS		
Soiled Bedding (SB) g N hd^{-1}	5102	3241
Livestock g N hd^{-1} (c)	*12662*	*12934*
OUTPUT g N hd^{-1}	*17764*	*16176*
N % change - Housing	***- 21.9***	***- 29.7***

Estimated loss pathways 1 to 4 (1 = max loss - 4 = min loss)		
Livestock uptake	2	2
Seepage NH_4^+ and NO_3^-	4	3
NH_3 emissions	1	1
N_2O, N_2 emissions	3	4

ADAS Composting	**Straw Compost**	**Woodchip Compost**
Week 0 g N hd^{-1}	5102	3241
Week 31 g N hd^{-1} (d)	*2740*	*3104*
N % change - Composting	***- 46.3***	***- 4.26***

Data in *italics* are estimates derived from IOTA (online)

(a) *Silage N content 2.58 % DM (Cattle silage 26.7 % DM content)*

(b) *Cattle concentrate N is calculated on (16 % CP) DM* (Dumont 2012)

(c) *Livestock N: Cattle 3.2 % N*

(d) *N loss from cattle composts is estimated by multiplying TN (g /kg) at week 31 by 60 % mass loss in straw composts and 25 % mass loss in woodchip composts. Mass loss estimates are derived from IGER results*

3.3.6.6.3 IGER: Sheep treatments

IGER Sheep housing **INPUTS**	**Straw Bedding** g N hd^{-1} (n=32)	**Woodchip Bedding** g N hd^{-1} (n=32)
Bedding g N hd^{-1}	73.6	80.3
Forage DMi g N hd^{-1} (a)	*974*	*943*
10 % Feed refusal g N hd^{-1} (a)	*97.4*	*94.3*
Livestock g N hd^{-1} (b)	*1425*	*1426*
INPUT g N hd^{-1}	*2569*	*2543*
OUTPUTS		
Soiled Bedding (SB) g N hd^{-1}	*760*	*551*
Livestock g N hd^{-1} (b)	*1384*	*1405*
OUTPUT g N hd^{-1}	*2143*	*1955*
N % change - Housing	***- 16.6***	***- 23.1***
N Losses and Removals		
Seepage g N hd^{-1}	-	-
Livestock uptake g N hd^{-1} (b)	*- 41*	*- 21*
Discarded SB g N hd^{-1} (c)	-	-

IGER Sheep composting	**Straw Compost**	**Woodchip Compost**
Week 1 g N hd^{-1}	760	551
Week 32 g N hd^{-1}	466	575
N % change - Composting	**- 38.6**	**4.36**

Data in *italics* are estimates derived from IOTA (online)

(a) *Hay 1.80 % N (82.7 % DM content; Silage 2.3 3 % N (29.6 % DM content)*

(b) *Livestock N: 2.0 % N in sheep meat and 14.6 % N in wool (2.75 kg wool hd^{-1})*

(c) No soiled sheep bedding (SB) was discarded

3.3.6.6.4 IGER Cattle treatments

IGER Cattle housing **INPUTS**	**Straw Bedding** g N hd^{-1} (n=12)	**Woodchip Bedding** g N hd^{-1} (n=12)
Bedding g N hd^{-1}	1485	790
Forage DMi g N hd^{-1} (a)	*7766*	*7599*
10 % Feed refusal g N hd^{-1} (a)	*777*	*760*
Livestock g N hd^{-1} (b)	*10624*	*10800*
INPUT g N hd^{-1}	*20652*	*19950*
OUTPUTS		
Soiled Bedding (SB) g N hd^{-1} (c)	*8476*	*4507*
Livestock g N hd^{-1} (b)	*11872*	*12080*
OUTPUT g N hd^{-1}	*20348*	*16587*
N % change - Housing	***- 1.47***	***- 16.9***
N Losses and Removals		
Seepage g N hd^{-1}	13.8	200
Livestock uptake g N hd^{-1} (b)	*1248*	*1280*
Discarded SB g N hd^{-1} (c)	*2587*	*2444*

IGER Cattle composting	**Straw Compost**	**Woodchip Compost**
Week 1 g N hd^{-1}	5889	2063
Week 32 g N hd^{-1}	3077	2079
N % change - Composting	**- 47.7**	**0.74**

Data in *italics* are estimates derived from IOTA

(a) *Hay 1.80 % N (82.7 % DM content); Silage 2.33 % N (29.6 % DM content)*

(b) *Livestock N: Cattle 3.2 % N*

(c) *50 % approx. of soiled cattle beddings (SB) were discarded before composting. Output SB g N hd^{-1} is estimated by SB mass multiplied by week 1 g N /kg.*

3.4 Discussion

Following HCC's conclusions and practical recommendations for the suitability of woodchip as a livestock bedding drawn from the housing trials carried out at ADAS and IGER, this discussion evaluates the influence of each site's *a priori* variable on the beddings, and their subsequent composting performance, before expanding into a more general discussion of the changes in nutrient concentrations during composting. The discussion is then concluded with an appraisal of the nitrogen budgets.

Housing trials

The eight week housing trials undertaken by ADAS and IGER, as well as anecdotal evidence from the demonstration farms across Wales concluded that generally woodchip can be an effective bedding material under cattle and sheep. Standards of animal health, welfare and cleanliness were reported to be as high on woodchip as on straw (HCC, 2008). Although, more woodchip bedding was needed under animals fed silage than hay. Older livestock appeared to perform well, but there were indications woodchip bedding did not suit finishing lambs (HCC, 2008). Given the free-draining nature of woodchips, it was recommended for use on concrete floors, preferably with effluent drainage capture system underneath, as seepage from hard-core or soil surfaces may pollute surrounding watercourses. For both cattle and sheep an initial 10cm layer of woodchips is preferable, as the manure and bedding did not integrate well, so an excessive under-layer is wasted. Furthermore, unlike manured straw bedding that quickly transfers to the animal's fur, woodchip's abrasive texture meant, that although the bedding appeared heavily manured, the livestock did not; so farmers were recommended to follow the appearance of the livestock rather than the bedding surface in determining when to apply top-ups (HCC, 2008). This is both an important economic factor and the reason why IGER required a second delivery of woodchips after 5 weeks (see 'Protocol anomalies' in section 3.2.1.2).

Water retention characteristics (ADAS)

The capacity of woodchip to absorb moisture is fundamental to its usefulness as a livestock bedding material. In an indoor bedding context, chips with the maximum water storage capacity should be chosen to reduce seepage volumes and the depth of bedding needed (i.e. creating environmental and economic benefits). It would also be desirable from an end- and interim-use perspective (e.g. thermophilic composting, fertiliser value) to maximise the nutrient content of woodchip during use. The key parameters of interest include the speed (rate) with which the material is able to absorb moisture and the quantity of moisture the woodchip is able to absorb (capacity). The water absorbency test results (section 3.3.2.1 and Appendix I) show that during the first hour of wetting, raw woodchips with a low initial moisture contents absorbed significantly more moisture, and at a faster rate than initially wetter woodchips. However, the results also indicate that if the woodchip become too dry (<5 % moisture), hydrophobicity and water repellency occurs, a property which is undesirable in the context studied here. The water drop penetration test (WDPT) results (see Figure 3.6) show that hydrophobicity initially inhibits water absorption in dry woodchips to a similar extent as those with a ≥30 % initial moisture contents. However, it should be noted that achieving moisture content of <5 % would be difficult in most conventional on-farm chipping scenarios without investment in, for example, forced-air drying technologies. Conversely, it could become an issue if the wood was sourced from reclaimed dry or heat-treated household timber. However, as hydrophobicity is a relatively short lived phenomenon (<1 h) this negative effect would only be of significance in the first few days of housing, until all the woodchip bedding had re-hydrated. Furthermore, the hydrophobicity response may be lessened by the high osmotic content and warm temperature of urine which would lower droplet surface tension. Overall, the woodchips have a low water retention capacity in comparison to other materials (e.g. smectite, waste paper pellets) due to the lignin-induced physical rigidity of the material. It could be possible to improve the water uptake properties of the woodchip by dilution with other materials, or by mechanically disrupting the woodchips to create planes of weakness for greater expansion/swelling on contact with water, in addition to promoting N ingress into the centre of the woodchip, facilitating its subsequent composting.

The cattle woodchip data (see Figure 3.8) suggest ca. 70 % MC is the maximum absorbency capacity of woodchips under indoor livestock housing conditions. Therefore, the W34 treatment absorbed an additional 95 %, compared to only 30 % and 26 % in the W53 and W55 treatments respectively. Although the capacity percentages are different, the pattern of these results reflects those found in the water absorbency experiment conducted in the laboratory. So on the strength of this evidence, it is reasonable to conclude that drier woodchips have the capacity to absorb greater amounts of excretal liquid and are therefore are more efficient as a bedding material, facilitating greater microbial activity (evident from higher compost temperatures (Figures 3.1 and 3.2)). However, the advantages of greater nutrient retention in the W34 over the W53 and W55 treatments during housing were less evident during the composting phase, than the physical differences inherent within the W53 treatment. The flat, large shaped chips in W53 compacted, creating a capping effect which trapped the manure on the surface of the bed. On the one hand, this development may have been beneficial in trapping liquids long enough to allow increased absorption into the bedding beneath, however this could be negative for livestock welfare and bedding cost. There is no evidence of W53 treatments requiring more frequent top-up bedding (see Table 3.16); however, removal of manure from the feed area may have affected this response. Table 3.15 estimates that 151 kg of manure was removed from C53 compared to none from the C55, yet C53 received 18 kg more bedding. Although, the absorptive advantage from the manure being trapped above the W53 bedding will have been counteracted by far greater quantities of N loss via NH_3 volatilization. This physical anomaly in the W53 treatment is fortunate in adding to our understanding of woodchip as winter animal bedding. By contrast, the square shaped W34 and W55 woodchip beddings were more mobile, allowing feed and excreted solids to become integrated, but also causing urine to pass through more quickly. Therefore, differences in available nutrients between W34 and W55 are more representative of the comparative absorbency capacities than between W34 and W53 treatments.

Optimising moisture availability during composting is essential to ensure that either microbial desiccation or anaerobic conditions do not prevail. It is unfortunate that the moisture content gradient of the raw bedding used in these trials were confounded by differences in source material, preventing a robust analysis of this factor. Despite this, some general observations can be made. During the composting phase, significant amounts of moisture were lost in some treatments. This can be ascribed to the initial composting temperatures exceeding 70° C, resulting in the loss of water vapour (e.g. ADAS sheep W34). In contrast, when composting failed to achieve high temperatures (e.g. ADAS sheep W53) moisture contents were seen to increase. This is likely to have arisen from the breakdown of labile material in the manure, releasing water which was not subsequently evaporated (via hydrolysis reactions). In broader terms, decomposition rate (compost temperature) and nutrient retention within the bedding-composts, is determined by the balances and resulting interaction of not just moisture contents, but also oxygen levels, particle surface area and the chemical properties of the feed-stocks. However, compared to straw-based composts, results show the nutritional advantage, absorbed by the W34 treatment compared to W53 and W55 during housing, was too small to significantly alter its overall composting performance in light of the more fundamental nutrient deficiency in the wood-based composts and percentage of wood within each woodchip compost (B:M ratio).

Dietary inputs (IGER)

With the exception of greater nitrate concentrations at week 1 (after housing) in silage fed treatments and lower pH in hay treatments at week 32 (after composting), the results in Table 3.43 and Table 3.57 show the different feed types had no significant influence on nutrient concentrations in compost at week 1 or at week 32. It should be noted that generally, however, nutrient contents in silage-fed treatments were higher than those in hay-fed, consistent with the livestock's DMi d^{-1} shown in Table 3.6. This balance of nutrient inputs between the feed-based composts is due to IGER's *ad libitum* feeding protocol, resulting in the animals satisfying their daily nutritional and energy demands as required, notwithstanding variations in the livestock's metabolic capabilities and quantities of extractable nutrients in each feed type. Furthermore, cattle fed wet silage produced a greater volume of urine than those fed hay – the total volume of seepage captured from CSC was 600 litres compared to 250 litres from CHC (see Table 3.64), however, the amounts of liquid absorbed by the cattle woodchip treatments were similar – moisture content of CSC and CHC composts after housing was 65.8 and 65.0 % respectively (see Figure 3.11). This tells us that even the woodchips under cattle fed a dry hay diet had reached their maximal water absorbance.

Nutrient dynamics during composting

The regression lines in Figures 3.17 and 3.75 show nitrification occurring over time in straw composts, but only up to week 4 (ADAS) and week 11 (IGER) in the woodchip treatments (note: NO_3^- levels in ADAS woodchip at week 0 show more influence from the inclusion of 2 week old sheep fractions than from the straw composts at this point). After weeks 4 and 11, nitrate levels in the wood-based composts decreased to near zero by the end of composting. The reason for this reversal is clear when seen in relation to NH_4^+ levels over the same period. Figures 3.19 and 3.20 (ADAS) and 3.78 to 3.80 (IGER) show NH_4^+ concentrations quickly decreased from week 0 to weeks 4 and 11 respectively, because of nitrification, immobilization or loss as gas or liquid. When viewed in unison, Figures 3.17 to 3.20 (ADAS) and 3.75 to 3.80 (IGER) show that as decreasing NH_4^+ levels cross with increasing concentrations of NO_3^- ca. weeks 4 and 11. Microbes are forced to convert NO_3^- back into NH_4^+ for growth and function - a process that requires a lot of energy. As levels of DOC and TSN are both already low, microbial activity is limited and the composting process slows dramatically. This hypothesis is supported by Rosswall (1981):

> *Microorganisms generally prefer ammonium as a nitrogen source, and their ability to use nitrate is restricted. Of the 2500 genera of fungi described, only 20 have been reported to assimilate nitrate (Payne, 1973; Downey, 1978). The occurrence of nitrate assimilation in bacteria seems to be more common than in fungi, although it is in no way ubiquitous (Hall, 1978). Since the assimilatory nitrate reductase is repressed by ammonium (Gottschalk, 1979), the latter is the preferential nitrogen source for microorganisms.*

The ratios of manure, woodchip and straw within the collective of composts that make up each livestock treatment are considered to be the reason why the process is delayed in the sheep treatment, which achieved higher levels of nitrification than cattle and microbes did not need to assimilate nitrate until after week 12.

The ratio of DOC to TSN or available C:N (AC:N) is an important parameter in composting, particularly in the present project, where levels of both AC and AN were critically deficient in wood-based treatments at both trial sites. Enzymatic breakdown of compost solid surfaces release nutrients into the matrix; a proportion of these available nutrients become assimilated by microbes for biological function, while the rest remain in solution and are constantly transformed and recycled over time. However, for the process to be sustained, microbes must have AC and AN - fundamental nutrients for growth, reproduction, respiration and energy - in a ratio of ≤ 25:1. At higher ratios, the proportion of AN immobilized by microbes increases (compared to AC), resulting in less AN for microbial activity (i.e. protein synthesis), causing temperatures within the compost to drop and the decomposition process to slow. Conversely, when AC:N is < 25:1, there is sufficient N available for microbial growth and activity, so the excess ammonia-N is susceptible to loss as gaseous NH_3, liquid NH_4^+, or, after nitrification as NO_3^- as N_2O and N_2 if the whole, or parts of the compost become anaerobic. In the present study, levels of available N in the woodchip composts are critically deficient. However, AC:N ratios are still <10:1 throughout composting, because available C is concurrently deficient, resulting in small amounts, but nevertheless a high percentage of available N remaining in the compost solution and so at risk of being lost (because of the microbial requirement of AC and AN in a set ratio, regardless of the size of the available N pool). Conversely the straw composts have similar AC:N ratios (Figures 3.29, 3.30 and 3.93, 3.94, 3.95) throughout composting and loss of N is high, but, levels of NO_3^- increase linearly throughout composting see ADAS Figure 3.17 and Table 3.27 and IGER Figure 3.75 and Table 3.46.

Ammonia volatilisation is strongly pH-dependent. In theory, at temperatures ≤ 25° C, NH_3 and NH_4^+ are in equilibrium at ca. pH 9.0, and higher pH favours gaseous formation and loss of NH_3. However, in reality, the NH_3 and NH_4^+ equilibrium depends much more on the physical dynamics and chemical properties of the particular compost matrix. Therefore, with pH generally above 8.0 in most of the treatments, most of the time, and temperatures predominantly ≥ 40° C for the first 130 days, conditions are likely to have caused substantial NH_3 emissions. Tiquia and Tam (2000) and Raviv et al. (2002) are representative of the consensus view that this is a significant loss route for NH_4^+ without the corresponding mass balance increase of NO_3^-. The high pH levels recorded in this study would indicate NH_3 volatilisation was a significant N loss pathway.

ADAS treatments were not acidic at any time during composting, and – with the exception of the SHC compost treatment between weeks 21 and 27; neither where the IGER treatments. This would inhibit the emergence of common white-rot fungi species such as *Phlebia radiate* and (particularly) *Phanerochaete chrysosporium* as DeForest et al. (2004) and Niku-Paavola et al. (1988) report these species' optimal activity range is limited to pH 3 - 4.5. However, many species of ammonia-assimilating fungi exist, some of which thrive in neutral-alkaline conditions. Soponsathien (1998) identified *Coprinus* spp., *L. tylicolo* and *T. tesquorum* as succeeding in neutral-alkaline conditions. In addition, Yamanaka (2003) reported that *P. urinophila* grew well even at pH 9.0. Therefore while resource competition is typical between bacteria and fungi, in this instance, both domains will have immobilized significant percentages of inorganic N; adding to losses as NH_3.

pH changes during composting

An increase in pH values up to 9.0 are not uncommon in successful composting (Sundberg et al., 2004; Ogunwande et al., 2008), and even pH values as low as 6.5 should not inhibit composting (Sundberg et al., 2004). The pH values in the present project are in line with these previous studies. pH fluctuates in the early stages of composting as different biochemical processes prevail at weekly or even daily timescales. For example, Nakasaki et al. (1992) and Tuomela et al. (2000) state that there is usually a drop in pH once organic material begins to decompose, promoting the production of organic acids as seen in the present project with pH lowest at weeks 4 to 6. Paillat et al. (2005) found pH decreased in composts with high NH_3 emissions, which is supported in findings by Helyar (1976) that nitrification also lowers pH. It is proposed that all three of these factors had varying responsibility in determining the drop in pH seen over the first 4 to 6 weeks at both trial sites. Gibbs et al. (2000) reported that turning the compost exposes fresh material for microbial colonisation and leads to the release of NH_3 that has accumulated in the internal void spaces of manure stacks, so increasing pH. This is evident in the present study in IGER cattle and straw treatments between weeks 3 and 11, when NH_3 emissions would have been greater than during the latter stages of composting. Ogunwande et al. (2008), approached the issue from reverse, by reporting that a decrease in pH can result from a decrease in turning frequency, which is evident in ADAS composts after week 20. Said-Pullicino et al. (2007) state that drops in pH are usually associated with anaerobicity, but only the straw treatments showed periodical anaerobicity in this study - although small anaerobic pockets at the centre of the woodchip piles cannot be ruled out. Furthermore, if anaerobic pockets were present, it is possible that some NO_3^- was denitrified to N_2O and N_2.

Electrical conductivity during composting

Electrical conductivity (EC) of the compost solution is a very informative, though non-specific, assessment of soluble salts concentrations and is therefore a useful indicator of compost's nutritional value to plants over the immediate to short term. The critical upper limits are between 3 and 5 mS cm^{-1} and are similar for both soils and plants.

EC readings at both experimental sites show the woodchip treatments increased during housing due to the addition of manure, from 0.12 mS cm^{-1} (mean EC in raw woodchips from both sites) to 2.55 mS cm^{-1} at ADAS and 4.29 mS cm^{-1} at IGER, but then remained unchanged until the end of composting 2.79 mS cm^{-1} at ADAS and 4.19 mS cm^{-1} at IGER. The difference between the two sites' EC readings is likely to be incidental, due to ADAS removing manure from behind the feed face where livestock predominately defecate/urinate while eating, so less excrement entered the compost matrix, even though IGER used 100 % more woodchip bedding, under 2 fewer cattle $treatment^{-1}$.

As previously discussed, the initially drier W34 at ADAS absorbed more excretal liquids during housing than the W53 and W55 treatments and consequently, is expected to contain and maintain higher EC readings during composting. However, EC in W34 only increased by 0.67 mS cm^{-1}, compared to 0.65 in W55 and -0.59 in W53 (see Tables 3.23 and 3.39 and Figure 3.39); illustrating the absorptive advantage gained by lower initial MC was almost completely lost within the broader context of nutrient deficiency - primarily the low concentrations and proportionate availability of C and N; lack of cation exchange sites and physical properties of the wood-based composts.

In contrast, EC measurements in straw treatments increased throughout composting. At ADAS, EC in raw straw was 3.36 mS cm^{-1} then 6.45 mS cm^{-1} after housing and 11.3 mS cm^{-1} after composting. Similarly, EC in IGER's raw straw was 3.7 mS cm^{-1} then 7.46 mS cm^{-1} after housing and 14.7 mS cm^{-1} after composting. This shows, first, that EC increase from manure inputs during housing, was equivalent under both bedding types, which is expected because DMi and animals pen^{-1} were replicated in each livestock treatment; second, that soluble salt concentrations in the straw treatments increased by approximately 100 % during composting at each site, even though significant amounts will have been leached (K, Na, Ca, NH_4^+ and NO_3^-), NH_4^+ immobilized and emitted as NH_3 and some NO_3^- denitrified - highlighting straw compost's performance. Whereas, EC readings in the woodchip treatments, show losses were counterbalanced by quantities made available by microbial decomposition. In other words, the woodchip compost's fertility value (measured by soluble salt content) did not increase during the 8 month composting period. This conclusion is of critical importance in determining how to manage soiled woodchip bedding.

Phosphorus dynamics during composting

Previous studies have indicated that phosphorus levels generally drop during composting (Sommer, 2001; Larney et al., 2008b). Larney et al. (2008b) also noted significantly different P concentrations in straw and woodchip bedding (woodchip having a higher start concentration), and that losses during composting were not significantly different between the two bedding types, which is in agreement with the results presented here. Barnett (1994) reported total P concentrations in dairy cattle manure of approx. 6.37 g kg^{-1} and 6.57 g kg^{-1} within sheep manure, similar to straw treatments at ADAS (Table 3.40) and IGER (Table 3.57) while Bremer et al. (2008) found soluble P accounted for 28 % of total P in cattle manure, similar to the 26.7 % in IGER's woodchip treatment at week 32 but otherwise approx. 10 – 20 % higher than all other treatments after composting, which might be expected when comparing uncomposted to composted samples. Larney (2008a) states the reason for increased extractability of P in the presence of wood chips is unclear. However, Miller et al. (2003) found that higher calcium content in straw than wood chips (1.0 vs. 0.4 g kg^{-1}) and hypothesized that may have caused increased phosphate precipitation, reducing extractability in manure mixed with straw bedding.

Potassium, sodium and calcium dynamics during composting

Due to high concentration of K in plant material (ca. 80-100 mM in cell sap) and the relatively low K demand of animals, K is typically excreted in large concentrations by both sheep and cattle (personal communications D. L. Jones). Within urine, potassium is predominantly present in a soluble mineral form (e.g. $KHCO_3$), which is both available to plants but also prone to leaching during composting and after application to soil (Zarabi and Jalali, 2012). Within compost or solid faecal material, a large proportion of the K is present as free K^+, however, a small proportion of the total K is also occluded in undigested plant material and immobilised in microbial cells. Excess K can potentially interfere with the absorption of other nutrients and micronutrients, so a balance, particularly of K:Ca, is critical. However, the results suggest woodchip derived composts contain a good balance of K and Ca (13:1 at ADAS and 9:1 at IGER). As K is only taken up in small amounts by the microbes, K concentrations (expressed on a weight basis) should progressively increase during composting, which is generally the case in IGER's range of treatments (see Figure 3.117), although notably K levels reduced in the woodchip treatment during composting. The reductions seen in the ADAS composts (Figures 3.31, 3.32 and summarised in Figures 3.61, 3.62), would indicate that substantial losses in seepage had occurred. Further, the findings suggest that the IGER woodchip composts would contain a substantial amount of K if it were to be used at moderate application rates (10 t ha^{-1} equates to 28 kg K ha^{-1}) and of agronomic significance.

Sodium is an essential, but rarely limited, micronutrient for plants and microbes growing in agricultural soils. However, Na can replace some of a plant's K demand. For example, sugar beet (*Beta vulgaris*) usually takes up about 50 kg Na ha^{-1} from soil with sufficient K. This high uptake rate is an ancestral function within modern cultivars from its indigenous origins in sodium rich, maritime environments with only small quantities of K (The Potash Development Association (PDA), leaflet 12, 2006). Other crops require and remove somewhat less sodium. In sheep and cattle, sodium is used in saliva to neutralise the acids formed by bacteria in the rumen liquor. If animals experience Na deficiency, they automatically prioritize blood Na levels and substitute saliva Na with K, but this process reduces resorption of Mg, placing the animal at risk of hypomagnesaemia (PDA, leaflet 6, 2005). Na levels in the ADAS treatments were significantly higher in the raw straw than woodchip beddings, but the rate at which they decrease over time is determined more by the type of livestock manure than the bedding types (see Table 3.35). Na is particularly prone to leaching from composts and soils (Zarabi and Jalali, 2012; Wright et al., 2008). It should be noted, however, that if compost seepage is collected it can also be used a liquid fertiliser with minimal risk of environmental damage (Jarecki et al., 2012).

Calcium availability rarely limits agricultural production in lowland Welsh soils, as considerable amounts of Ca^{2+} are held on the soil' exchange complex, preventing them from leaching. In addition, regular liming of grassland and arable land at rates of 1-10 t $CaCO_3$ ha^{-1} has tended to replenish Ca removed in livestock production (as silage or in animals). There are no reported cases of low Ca^{2+} directly limiting composting or maturation or agricultural wastes; however, co-composting organic residues with lime often speeds up the composting of nutrient-imbalanced, metal contaminated or low pH wastes (Wang et al., 2008; Wong and Fang, 2000). Ca is an essential nutrient within plant cell wall structure and provides for normal transport and retention of other elements, as well as strength. It is also thought to counteract the impact of alkali salts and organic acids within a plant. Losses of Ca by precipitation (e.g. $CaCO_3$, $Ca_3(PO_4)_2$) or leaching are uncommon in soil and composts due to sorption of Ca^{2+} to negatively charged cation exchange sites on the solid surfaces. This displacement of H^+ helps maintain a high pH (it was >7.5 throughout the 8 month composting period) (Brady and Weil, 2008). Although not specifically investigated here, it is suspected that, unlike composts derived from green waste and biosolids, the cation exchange capacity (CEC) of the woodchip-derived composts was very low. If the woodchips had decomposed fully then they would have a high CEC (Jokova et al., 1998); however, that was not the case in these trials and it is suggested limited cation exchange sites in wood-based composts became quickly saturated, and subsequently, substantial quantities of cations were leached. This is supported by Lunt (1961) who showed that woodchips add to soil did not increase the soil's CEC.

However, increasing the surface area of woodchips by crushing them, or mixing with sawdust, could – depending on co-composted materials – increase CEC significantly, as shown by Sanchez-Cordova et al. (2008). However, as with K and Na, in the absence of any negatively charged colloids, the overall decrease in soluble Ca^{2+} is most likely due to leaching and, to a lesser extent, to microbial immobilization. Immobilization is postulated because Tables 3.36 (ADAS) and 3.55 (IGER) show that soluble Ca^{2+} does not decrease linearly, but fluctuates, especially between weeks 0 – 12; the most biologically active phase of composting (see accompanying Figures 3.35 – 3.36 and 3.102 – 3.104) .

Nitrogen loss pathways

Average estimated N losses from woodchip treatments across both trial sites were highest during housing: 33 % compared to a net N increase of 1.3 % during composting. In contrast, straw treatments lost 25 % of initial N during housing and 42 % during composting (see section 3.3.6.6). These estimates generally agree with other studies comparing straw and woodchip beddings. In a cattle-only study, Hao et al. (2004) reported higher N loss from straw-bedded manure composts (42 %) and smaller loss (12 %) from woodchip. Eghball et al. (1997) also reported N losses of between 19 % and 42 % N from cattle manure. It is suggested the high estimated N losses from both bedding types during the ADAS sheep housing trial were due to a combination of the high stocking rate (30 pen^{-1} at 1.03 m^2 hd^{-1}) and N content (18 % crude protein) in the concentrates fed on a daily basis. Therefore, the estimates are considered to be in the correct range. To support this claim, ADAS cattle-woodchip treatments (which were also fed concentrates) lost 30 % of initial N during housing, compared to 17 % from IGER's woodchip beddings. Differences in bedding mass hd^{-1} between the two sites (ADAS 336 kg hd^{-1} DM vs. 560 kg hd^{-1} DM at IGER) and IGER's data including 50 % hay fed cattle, are both factors likely to have contributed to lower N losses at IGER. Although both Dumont (2012) and Chadwick (personal communications) state that larger area allowances (m^2 hd^{-1}) increase NH_3 emissions (due to a greater exposed surface area), and section 3.3.6.1 shows IGER's cattle and sheep had greater area allowances than ADAS livestock, it is not possible, without a balanced comparison of housing protocols, bedding mass and livestock pen^{-1}, to estimate loss levels by area allowance.

During storage and decomposition of manure solids, N is lost in gaseous and liquid forms that contribute strongly to the debit side of nitrogen balance-sheets. Gaseous as well as leaching losses are highest at the beginning of the decomposition and decrease with time (Eghball, 1997). Both are affected by temperature, B:M ratio, pH, initial N-content and compost turning frequency (Jones, 2004). Dewes (1995) reported gaseous N losses to be far higher than liquids, following a

177 day experiment with cattle manure - only 2.5 % to 3.4 % of the initial N was lost in liquid form, but 25 % to 44 % was lost as ammonia. Further, Eghball (1997) calculated that 92 % – 95 % of TN loss was volatilized as NH_3 in contrast to < 0.5 % as inorganic N in seepage.

Denitrification can occur during composting, although it is of much less significance as an N loss pathway in comparison to NH_3 volatilisation (Maeda et al., 2010). The denitrification of oxidised nitrogen (NO_2^- and NO_3^-) into N_2O and N_2 is, by definition, an anaerobic process, only possible after nitrification has taken place under aerobic conditions. Therefore, it is considered denitrification as an N loss pathway in woodchip composts was limited by a combination of the very low nitrate levels and the material's porosity that maintained airflow. Luo and Saggar (2008) reported denitrified N losses of only 0.01 % from cattle manure deposited on out-winter woodchip pads (OWPs). As these are exposed to winter rainfall, there is a greater potential for anaerobic conditions to develop due to water-logging. In contrast, Moral et al, (2012) reported N losses (as % of initial total N) from soiled cattle (fed silage and concentrates) straw bedding-composts, established in early July, as; 1.5 % emitted as NH_3; 1 % as N_2O and 5.2 % as N_2. The study reasoned that the loss profiles were predominantly due to anaerobic conditions developing in the middle and lower areas of the heaps, as well as compost temperature and rainfall. Consequently, it is assumed that denitrified N losses from indoor woodchip beddings are at or lower than 0.01 %.

However, anaerobic conditions (O_2 < 5 %) did develop in the ADAS cattle straw compost after nitrification had taken place; under these circumstances, denitrification may account for as much as 3-5 % N being lost as N_2O and N_2. During a six week soil-manure incubation study, Calderon (2004) showed that as much as 5 % of N was denitrified; linking these two studies, Thorman et al. (2006) suggested that efforts to conserve mineralised N during composting may only result in greater amounts of denitrified N when the material is applied to the soil.

Estimated inorganic N losses from ADAS and IGER's woodchip composts are broadly in line with the findings of Hadas and Portnoy (1994) that reported AN losses of 11 % to 29 % of TN after 32 weeks' composting. Ammonia volatilization is considered to be the most prevalent N loss pathway from both bedding types during housing and from straw during composting, although denitrified losses are considered to have played an increasingly important role, particularly in the cattle straw treatments, which became anaerobic due to compost compaction (Savoie et al., 1996; Amon et al., 2001).

The structural rigidity of woodchips appeared to limit integration of the manure and bedding fractions during housing, causing a stratified layering. It is expected that this exposed manure surface layer was significant in N volatilization from woodchip beddings during housing. Subsequently, AN levels in the wood-based composts were very low from the start, and after the initial microbial activity oxidised concurrently low levels of biodegradable C, decomposition slowed. The initial moisture content of the woodchips played an important role: the trials showed that only woodchips with initial MC < 50 % achieved UK PAS100 thermal kill temperatures, owing to greater capacity to absorb nutrient rich liquid during the housing period, facilitating higher levels of microbial activity during the first three weeks of composting. However, after eight months of composting the nutritional differences between all woodchip-based composts regardless of pre-treatments were negligible.

Clearly, the present study advocates composting as a means of managing, on-farm nutrient balances, as well as, weed seed and pathogen transfer. Shepard et al, (2002) listed the benefits of composting as follows;

- Reduction of substrate mass
- Improved friability and handling characteristics
- Destroys weed seeds and potentially harmful pathogens by generating high (60 – 70º C) temperatures
- Provides phyto-sanitary effects on incorporation into the soil
- Incorporates inorganic N into the organic fraction, thus protecting from immediate loss after application
- Reduces odour and ammonia emissions during land spreading
- Concentrates plant nutrients, enabling application rates to be lower and the risk of crop smothering to be reduced.

Compost management techniques, ranging from actively managed, frequently turned piles to simple stockpiles, play a major role in nutrient retention, conversion dynamics and ultimately the quality of the finished composted product. However, Moral (2012) highlight potential environmental impacts that arise from composting. They include diffuse pollution of water via leachate from storage heaps (Dewes et al., 1993) and NH_3 (Sommer et al., 2006), N_2O and methane (CH_4) emissions to the atmosphere (Chadwick et al., 2011). Both N_2O and CH_4 are potent greenhouse gases with global warming potentials of 297 and 25 times greater, respectively, than carbon dioxide (CO_2) (Forster et al., 2007). Environmental and management factors influence the extent of these losses, but more importantly, is the content and availability of nutrients within the material being applied to the land (Moral, 2012).

Nevertheless, there is an economic argument for not composting, by cutting out the associated management costs and allowing soil microbes to breakdown the material in situ (this approach is discussed further in section 5.4). However, applying non-composted soiled bedding to grazing land can lead to significant problems, in particular, the transfer of disease to healthy stock (Chambers et al., 2001), and therefore, should be avoided. To minimise the risk of transferring disease, Chambers et al. (2001) advocate that all slurries and solid manures (soiled bedding) should be stored for at least one month before land application, after which, pasture should not be grazed by adult livestock for 1 – 2 months, until all visible signs of solids have disappeared, and 6 months before grazing young stock that are more susceptible to infection.

3.5 Conclusions

- Woodchips with lower moisture content absorbed more liquid during housing.
- Woodchips with lower % MC reached higher temperatures during composting, which were sustained long enough to satisfy BSI PAS100 compost sanitization regulations.
- Anecdotal evidence suggested the physical shape of the woodchips influenced the interaction between the bedding material and manure fractions.
- Livestock numbers, area allowances and nutritional intakes were balanced within each livestock trial at IGER, so dietary inputs appeared to have little influence on composting performance, compared to bedding type, although differences were evident, in seepage volumes from hay- vs. silage-fed cattle treatments (600 L from silage-fed vs. 250 L from hay-fed treatments). However, although IGER and ADAS trials were incomparable, variations in IGER's feed-based compost seepage volumes were considered beyond the absorbency capacity of the ADAS cattle-woodchip beddings, as the moisture content of all three was 68 % MC ± 1 % at the start of composting.
- Estimated N losses (% N loss head^{-1}) were similar in both woodchip and straw beddings during the housing periods at both sites.
- Both woodchip and straw compost treatments had low AC:N ratios, but, critically, straw composts had AN concentrations in excess of microbial functioning requirements. Thus the excess was at risk of being lost to the environment, as estimated % N losses head^{-1} show in section 3.3.6. In addition, although deficient concentrations of both AC and AN in woodchip treatments, will have restricted microbial function (growth and activity). The AC:N ratios in woodchip composts were < 10:1; therefore a small quantity, but relatively high % of AN was still at risk of being lost to the environment.
- It is suggested that leaching of K, Na and Ca in seepage from both compost-bedding types was a major loss pathway. Nevertheless, decomposition of solids resulted in straw compost, EC readings increasing by 100 %, whereas decomposition in woodchip treatments was only sufficient to maintain EC readings at a constant level throughout the composting period.

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4.1 Introduction

The previous chapter detailed the nutrient dynamics within the straw-manure and woodchip-manure composts over 7 months (the compost having previously been used as livestock bedding). This chapter investigates the subsequent agronomic benefit of the material in a range of agricultural contexts.

In 2000, the World Resource Institute (NationMaster, 2012) ranked the UK seventh highest in terms of average chemical fertiliser use out of 138 countries (UK average use = 285.8 kg NPK fertiliser ha^{-1} $yr.^{-1}$ over 5.98 Mha of arable and permanent cropland, which equates to a total use of ca. 1.7×10^6 t NPK $yr.^{-1}$). Owing to the increased desire to develop more sustainable agricultural systems, there is an urgent need to improve fertiliser use efficiency in the UK. Part of the Woodchip for Livestock Bedding Project's mandate was to encourage the primary use of organic fertiliser in Wales, supplemented with chemicals if necessary (Paul and Beauchamp, 1994). Pot scale growth trials were carried out because of the concurrent demands of the WG project, resulting in the first two growth trials starting in November. In addition, limited space and funding did not allow plot scale field trials to be carried out at Bangor, as IGER and ADAS both carried out field trials, although their trials were non-replicated and designed for open day exhibition purposes. The results of these plot trials are presented, for reference only, in Appendix II. The growth trials described in this chapter aimed to establish and develop best practice guidelines on the most efficient and profitable end use of the woodchip-manure compost. To this aim, three greenhouse-based growth trials were carried out to address two key objectives:

1. To determine the optimum lifespan of the woodchip as a recyclable bedding and to assess its value as an organic fertiliser.
2. To establish the relative agronomic benefit of the 'fine' and 'coarse' fraction of the woodchip-derived compost to determine whether sieving the compost represents a worthwhile option for farmers to increase its fertiliser value.

To address the first objective, a grass-based trial was established to compare the relative agronomic performance of 1- and 3-year old woodchip-manure composts. For comparison, the trial included two control treatments: a conventional NPK inorganic fertiliser at a rate of 150-57-79 kg ha^{-1} respectively and a 'zero-addition' treatment which received no fertiliser. To address the second objective, two spring barley trials were carried out to establish whether there was any agronomic benefit to be gained from sieving the woodchip-manure compost to extract the fine, well-decomposed fraction that was thought to be more nutrient enriched. These latter trials were carried out because of concerns that the coarse woody fraction in the woodchip compost might lock up soil nitrogen when applied to land, reducing subsequent crop yield. To simulate commercial compost screening machines, an 8 mm sieve was used to separate the fractions. The < 8 mm material was mostly composed of composted manure and hay or silage feed with a small amount of wood. In contrast, the > 8 mm fraction was almost entirely made up of intact woodchips, which showed few, if any, visual signs of degradation. Both trials included the three parent compost amendments and their size defined fractions, three straw based amendments and two 3 year old woodchip comparisons, as well as control treatments: soil-only and conventional NPK. In the first of the two barley growth trials, compost amendments were applied at 100 t ha^{-1} and NPK at 221-84-116 kg ha^{-1}. In the second trial, conventional application rates were applied, compost at 10 t ha^{-1} and NPK at 150-57-79 kg ha^{-1}. These two trials are referred to as B100 and B10, respectively.

4.2 Methods

4.2.1 Experimental design

A factorial, randomised block design was used in each of the 3 trials, comprising 28 pots in the grassland trial and 64 pots in both the barley (10 and 100 t ha^{-1}) trials. All three trials were conducted in a temperature-controlled greenhouse with a minimum photoperiod of 16 hours d^{-1}, heated to maintain 20° C during daytime and 18° C at night, augmented as necessary by 400 W Sun SON-T horticultural lamps. Treatment pots in all three trials (as above) were positioned on an absorbent, felt covered bench in a central location in the greenhouse and lightly watered on a daily basis. It is expected that nutrient loss, particularly from the NPK control treatment, will have been considerable – although, regrettably, time constraints and WG project objectives did not allow the measuring and analysing of seepage volumes and nutrient contents to be included. However, it should be noted that generally the same amount of water was added to each pot within the randomised design.

4.2.2 Characterisation of soil

Typical brown earth topsoil (Eutric Cambisol, Denbigh Series) (Soil Survey of England and Wales; 1983), was used in all three pot trials. It was chosen as it represents a dominant soil type under lowland (< 500 m altitude) sheep and cattle grazing in Wales. Prior to sampling, the soil had received regular urine and faecal inputs from grazing sheep throughout the year. The soil had a sandy clay loam texture and was collected from the surface Ah horizon (5–20 cm) of a lowland (15 m altitude) freely draining, heavily sheep-grazed grassland which received regular fertilisation (120 kg N, 60 kg K and 10 kg P $yr.^{-1}$) at Bangor University's Henfaes research farm, Abergwyngregyn, Gwynedd (53º14' N, 4º01' W). However, in 2007, when the soil used in this study was collected, concomitant WG obligations and requirements did not allow the candidate to conduct soil analyses, so on the advice of D. L. Jones, analyses of the same field soil, taken the same year, by Dr. S. Lucas and published in (Lucas and Jones, 2009) were adopted and are represented in Table 4.1.

Table 4.1: Chemical and physical characteristics of the typical brown earth used in all three growth trials.

Soil analysis	Brown Earth
$EC_{1:1}$ (µS cm^{-1})	80 ± 4
pH($_{1:1}$ H_2O)	6.06 ± 0.07
$CaCO_3$ (g kg^{-1})	0.11 ± 0.02
Water holding capacity (g kg^{-1})	520 ± 20
Dry bulk density (g cm^{-3})	0.93 ± 0.03
Moisture content (g kg^{-1})	160 ± 10
Organic C (g kg^{-1})	2.1 ± 0.1
Total N (g kg^{-1})	0.16 ± 0.01
C:N ratio	13.3 ± 0.6
Soil solution NO_3^- (mg N l^{-1})	13.7 ± 1.3
Soil solution NH_4^+ (mg N l^{-1})	1.4 ± 0.1
Exchangeable cations	
Na (mg kg^{-1})	29 ± 3
K (mg kg^{-1})	116 ± 18
Ca (mg kg^{-1})	1595 ± 217
Mg (mg kg^{-1})	89 ± 19
Al (mg kg^{-1})	22 ± 2
Extractable P (mg kg^{-1})	9.9 ± 0.3
Soil respiration (g CO_2 m^{-2} h^{-1})	0.6 ± 0.02

4.2.3 Determination of soil mass

Pots for the plant growth trial were prepared by mixing together the appropriate amount of compost and soil, placing the mixture in a plastic bag and shaking it to ensure homogenisation. The pots were then filled and seeds inserted by hand, 2 cm beneath the surface. The approximate soil mass in the pots was 1.35 kg pot^{-1} in the grass and barley B10 trials and 0.95 kg pot^{-1} in the barley B100 trial.

4.2.4 Determination of fertiliser application rates

The abbreviated term NPK is used to describe the pre-blended 21 % N : 8 % P_2O_5 : 11 % K_2O inorganic fertiliser (YaraMila®) Yara UK Ltd, Grimsby, UK, used in all three trials. A multiplier of 7.143 was determined to achieve an application ratio of 150-50-80 NPK, or as near as possible accounting for the pre-blend: 150-57-79 kg ha^{-1} (only N needs be calculated as P and K are ratio bound). Therefore, 1.022 g NPK fertiliser was applied pot^{-1}. The compost amendments were applied at a rate of 14.3 g pot^{-1} equivalent to 10 t ha^{-1}.

4.2.4.1 Grass trial

The grassland growth trial was conducted under glasshouse conditions, described in section 4.2.1, at Bangor University's Pen-y-Ffridd Field Station between 26th November 2007 and 14th April 2008 and consisted of seven treatments described in Table 4.2 replicated four times. Treatments include two topsoil controls: zero-addition and commercial NPK fertiliser applied in a single dose at a rate equivalent to 150-57-79 kg ha^{-1}. Compost amendments were all cattle-derived woodchip-manure, and included (1) ADAS C34 and C55, to elucidate whether the bedding's initial moisture contents influenced the subsequent fertility of the composts, and (2) IGER CSC containing the same component feedstocks - cattle (silage) manure and woodchip (Tables 4.2 and 4.3). Two further cattle woodchip-manure amendments were obtained from Glynllifon College and Pontbren Farmers' Group. Both had been composted in open-air piles for three years. The aim was to assess the fertility value of mature woodchip-manure products. Watering was carried out on a daily basis for 20 weeks, then the above-ground biomass was harvested and oven dried at 80° C for 48 h.

Topsoil and amendment nutrient contents are shown in Table 4.3.

Table 4.2: Abbreviations for amendments used in the grassland trial.

Treatments	Abbreviation
1. Topsoil only	Soil
2. NPK fertiliser (app. rate 150-57-79 kg/ha)	NPK
3. ADAS Cattle woodchip 34 %	W34
4. ADAS Cattle woodchip 55 %	W55
5. IGER Cattle fed silage on woodchip	CSC
6. Pontbren 3 year old woodchip	Pb3
7. Glynllifon 3 year old woodchip	Glyn3

Table 4.3: Nutrient content in Grass trial topsoil and amendments. Where two numbers are presented, the first represents the nutrient added in the amendment while the second represents the intrinsic available soil nutrient concentration.

Grass trial Treatments	Total C:N	Total N (mg /pot)	DIN (mg /pot)	P_2O_5 (mg /pot)	K_2O (mg /pot)
Topsoil *	13	187	17.7	11.6	136
NPK + Soil	4	215 +187	215 +17.7	81.8 +11.6	112 +136
ADAS C34 + Soil	41	135 +182	0.41 +17.1	4.91 +11.2	28.7 +132
ADAS C55 + Soil	43	142 +182	0.29 +17.1	8.00 +11.2	28.6 +132
IGER CSC + Soil	59	106 +182	0.52 +17.1	6.99 +11.2	32.5 +132
Pb3 + Soil	10	504 +182	1.56 +17.1	4.87 +11.2	45.1 +132
Glyn3 + Soil	ND	ND	ND	ND	ND

* Soil nutrient contents (Lucas and Jones, 2009)

4.2.4.2 Barley trial 1 (100 t/ha)

The B100 trial was conducted under glasshouse conditions at Pen-y-Ffridd Field Station between 17th July and 13th November 2007. The trial consisted of 16 treatments (Table 4.4) each with 4 replicates. These included two topsoil control treatments: a zero-addition and a conventional NPK fertiliser, applied in a single dose at a rate equivalent to 221-84-116 kg ha^{-1}. The amendments included both sheep- and cattle-derived 1 year old woodchip composts (Treatments 3 - 11) and two, 3 year old woodchip composts obtained from Glynllifon and Pontbren (Treatments 15 - 16). For comparison, three, 1 year old, straw-based compost amendments were included (Treatments 12 - 14). The project's woodchip composts were sieved through an 8 mm mesh to obtain the two size fractions (< 8 mm and > 8 mm). Each pot was planted with 4 barley seeds. The same pre-blended NPK was used in this trial as in the grass trial, but was applied at a single dose rate of 1.51 g NPK pot^{-1} to reflect the increasing N demand of cereals. The compost was applied at a rate of 100 t ha^{-1}, equivalent to 143.1 g compost pot^{-1}. Amendment nutrient contents are shown in Table 4.5. Nutrient contents varied depending on the different compost bulk densities and, as a result, the mass of soil added.

Table 4.4: B100 growth trial, compost amendments, associated abbreviations and group definitions

Treatments	Abbreviation	Group
Topsoil only	Soil	Controls
Nitrogen-Phosphorus-Potassium fertiliser	NPK	
ADAS Cattle woodchip 55 %	ADAS C55	
IGER Sheep fed hay on woodchip	IGER SHC	Parent compost
IGER Cattle fed silage on woodchip	IGER CSC	
ADAS Cattle woodchip 55 % (> 8 mm)	ADAS C55 > 8	
IGER Sheep fed hay on woodchip (> 8 mm)	IGER SHC > 8	Large fraction
IGER Cattle fed silage on woodchip (> 8 mm)	IGER CSC >8	
ADAS Cattle woodchip 55 % (< 8 mm)	ADAS C55 < 8	
IGER Sheep fed hay on woodchip (< 8 mm)	IGER SHC < 8	Small fraction
IGER Cattle fed silage on woodchip (< 8 mm)	IGER CSC < 8	
ADAS Sheep straw	ADAS SS	
ADAS Cattle straw	ADAS CS	Straw
IGER Sheep fed hay on straw	IGER SHS	
Pontbren 3 year old woodchip	Pb3	3 year old
Glynllifon 3 year old woodchip	Glyn3	

Table 4.5: Nutrient content in B100 trial topsoil and amendments. Where two numbers are presented, the first represents the nutrient added in the amendment, while the second represents the intrinsic available soil nutrient concentration.

B100 trial	Total	Total N	DIN	P_2O_5	K_2O
Treatments	C:N	(mg /pot)	(mg /pot)	(mg /pot)	(mg /pot)
Topsoil *	13	187	17.7	11.6	136
NPK + Soil	4	316 +187	316 +17.7	121 +11.6	166 +136
ADAS C55 + Soil	43	1422 +128	2.92 +12.1	80.0 +7.91	286 +92.7
IGER SHC + Soil	42	1433 +128	42.4 +12.1	74.8 +7.91	369 +92.7
IGER CSC + Soil	59	1058 +128	5.21 +12.1	124 +7.91	325 +92.7
ADAS C55 >8 + Soil	58	1064 +128	2.19 +12.1	60.0 +7.91	275 +92.7
IGER SHC >8 + Soil	54	1082 +128	12.4 +12.1	58.8 +7.91	406 +92.7
IGER CSC >8 + Soil	64	994 +128	4.88 +12.1	63.2 +7.91	304 +92.7
ADAS C55 <8 + Soil	21	2589 +128	5.33 +12.1	145 +7.91	321 +92.7
IGER SHC <8 + Soil	22	2787 +128	25.5 +12.1	137 +7.91	225 +92.7
IGER CSC <8 + Soil	27	1938 +128	9.51 +12.1	164 +7.91	324 +92.7
ADAS SS + Soil	16	3190 +68.4	221 +6.45	97.9 +4.23	630 +49.6
ADAS CS + Soil	11	4112 +68.4	260 +6.45	64.0 +4.23	784 +49.6
IGER SHS + Soil	13	3959 +68.4	250 +6.45	80.9 +4.23	1870 +49.6
Pb3 + Soil	10	5036 +128	15.6 +12.1	48.7 +7.91	451 +92.7
Glyn3 + Soil	ND	ND	ND	ND	ND

* Soil nutrient contents (Lucas and Jones, 2009)

4.2.4.3 Barley trial 2 (10t/ha)

The B10 trial was conducted under glasshouse conditions as described in section 4.2.1 at the Pen-y-Ffridd Field Station between 30th November 2007 and 28th March 2008. The trial consisted of 16 treatments (Table 4.6) each with 4 replicates. These included two topsoil control treatments; a zero-addition and a pre-blended NPK fertiliser, applied in a single dose of 1.02 g NPK pot^{-1}, equivalent to 150-57-79 kg ha^{-1} (the same as the grass trials). The amendments included both sheep- and cattle-derived 1 year old woodchip composts (Treatments 3 - 11) and two, 3 year old woodchip composts obtained from Glynllifon and Pontbren (Treatments 15 - 16). For comparison, three, 1 year old, straw-based compost amendments were included (Treatments 12 - 14). The project's woodchip composts were sieved through an 8 mm mesh to obtain the two size fractions (< 8 mm and > 8 mm). Each pot was planted with 4 barley seeds. The compost was applied at a rate of 10 t ha^{-1}, equivalent to 14.3 g compost pot^{-1}. Amendment nutrient contents are shown in Table 4.7. Nutrient contents varied depending on the different compost bulk densities and, as a result, the mass of soil added.

Table 4.6: B10 growth trial, compost amendments, associated abbreviations and group definitions.

Treatments	Abbreviation	Group
Topsoil only	Soil	Controls
Nitrogen-Phosphorus-Potassium fertiliser	NPK	
ADAS Cattle woodchip 34 %	ADAS C34	Parent compost
ADAS Cattle woodchip 55 %	ADAS C55	
IGER Cattle fed silage on woodchip	IGER CSC	
ADAS Cattle woodchip 34 % (> 8 mm)	ADAS C34 > 8	Large fraction
ADAS Cattle woodchip 55 % (> 8 mm)	ADAS C55 > 8	
IGER Cattle fed silage on woodchip (> 8 mm)	IGER CSC >8	
ADAS Cattle woodchip 34 % (< 8 mm)	ADAS C34 < 8	Small fraction
ADAS Cattle woodchip 55 % (< 8 mm)	ADAS C55 < 8	
IGER Cattle fed silage on woodchip (< 8 mm)	IGER CSC < 8	
ADAS Sheep straw	ADAS SS	Straw
ADAS Cattle straw	ADAS CS	
IGER Cattle fed hay on straw	IGER CHS	
Pontbren 3 year old woodchip	Pb3	3 year old
Glynllifon 3 year old woodchip	Glyn3	

Table 4.7: Nutrient content in B10 trial topsoil and amendments. Where two numbers are presented, the first represents the nutrient added in the amendment, while the second represents the intrinsic available soil nutrient concentration.

B10 trial Treatments	Total C:N	Total N (mg /pot)	DIN (mg /pot)	P_2O_5 (mg /pot)	K_2O (mg /pot)
Topsoil *	13	187	17.7	11.6	136
NPK + Soil	4	215 +187	215 +17.7	81.8 +11.6	112 +136
ADAS C34 + Soil	41	135 +182	0.41 +17.1	4.91 +11.2	28.7 +132
ADAS C55 + Soil	43	142 +182	0.29 +17.1	8.00 +11.2	28.6 +132
IGER CSC + Soil	59	106 +182	0.52 +17.1	6.99 +11.2	32.5 +132
ADAS C34 >8 + Soil	53	110 +182	0.33 +17.1	4.03 +11.2	28.1 +132
ADAS C55>8 + Soil	58	106 +182	0.22 +17.1	6.00 +11.2	27.5 +132
IGER CSC >8 + Soil	64	99.4 +182	0.49 +17.1	6.32 +11.2	30.4 +132
ADAS C34 <8 + Soil	19	225 +182	0.68 +17.1	8.11 +11.2	30.9 +132
ADAS C55 <8 + Soil	21	259 +182	0.53 +17.1	14.5 +11.2	32.1 +132
IGER CSC <8 + Soil	27	194 +182	0.95 +17.1	16.4 +11.2	32.4 +132
ADAS SS + Soil	16	319 +176	22.1 +16.6	9.79 +10.9	63.0 +127
ADAS CS + Soil	11	411 +176	26.0 +16.6	6.40 +10.9	78.4 +127
IGER CHS + Soil	10	480 +176	17.5 +16.6	6.81 +10.9	173 +127
Pb3 + Soil	10	504 +182	1.56 +1.71	4.87 +11.2	45.1 +132
Glyn3 + Soil	ND	ND	ND	ND	ND

* Soil nutrient contents (Lucas and Jones, 2009)

4.2.5 Characterisation of meadow grass seed

EM1 Mixed meadow grass seed (Emorsgate Ltd, King's Lynn, Norfolk, UK) was selected for the grass trial. Considered a general purpose mixed grass seed containing: *Cynosurus cristatus* L. (crested dogstail, 50 %); *Festuca rubra* L. (slender creeping red fescue, 35 %); *Agrostis capillaris* L. (common bent, 10 %); and *Phleum bertolonii* (smaller cat's tail, 5 %), planted at a density of 4 g m^{-2} equivalent to 57.2 mg seeds pot^{-1}.

4.2.6 Characterisation of barley variety

The *Hordeum vulgare* L. cultivar variety *Optic* was chosen as it currently accounts for approx. 55 % of the malting barley market. *Optic* is considered to be disease resistant, and its short, strong straw avoids lodging (Encyclo, 2012).

4.2.7 Compost storage

At the end of the composting period, approx. 150 kg of each compost treatment was brought back to Bangor University in gas permeable 'Hippo' construction sacks (Waste Management Services Ltd., Chandlers Ford, Hampshire, UK) and stored at Henfaes research farm at 20° C. Subsamples (50 kg) were taken from most, but not all, compost treatments and stored at Pen-y-Ffridd glasshouse until required. It was considered that decomposition would be limited as far as practically possible under these conditions, although not eliminated.

4.2.8 Amendment selection

All 1 year old composts had to be woodchip-based, to test the agronomic benefit of annually sieving the soiled woodchip beddings. In addition, the selection of specific 1 year old composts used in the grassland and B10 trials was prioritised by determining differences in fertility resulting from the initial moisture contents of ADAS woodchip treatments and differences in fertility resulting from IGER's feed and livestock inputs in the B100 trial. Straw treatment selection aimed at limiting the differences between the wood and straw-based amendments to the bedding material itself, by selecting composts with similar dietary inputs. However, choice was limited. There was no choice of 3 year old composts, and NPK application rates were determined to maximise contrast in growth between the two controls; while the rates applied were high, they do fall within the common range applied across the UK. It is acknowledged, however, that DEFRA (2010) requires NPK applied to barley at rates ≥ 100 kg N ha^{-1} to be split into two doses. This is an error in the protocol for which the candidate takes full responsibility.

4.2.9 Preparation of compost amendments

After mixing the 50 kg bags of selected composts, approximately 3 kg was extracted by a series of gloved hand-grabs. In the laboratory, each 1 year old woodchip treatment was sieved through an 8 mm mesh, resulting in 12 – 25 % < 8 mm (by weight). To obtain the correct weight of woodchip-derived amendment per pot, composts were repeated quartered with a knife until the correct weights were achieved. These were then individually stored in the fridge until use. To obtain a representative quantity of straw and 3 year old woodchip, 1 kg of material was collected by gloved hand-grabs after vigorously mixing the material. This subsample was then repeatedly divided with a knife until the correct weights were obtained then stored in the fridge. NPK was weighed out: 1022 mg pot^{-1} for the grassland and B10 trials and 1506 mg pot^{-1} for the B100 trial.

4.2.10 SPAD chlorophyll readings

A Minolta SPAD 502 meter (Spectrum Technologies, Plainfield, IL) was used to measure the chlorophyll content in the top leaf of each plant. Research has shown that leaf chlorophyll content is closely correlated to levels of nitrogen in the plant, and consequently SPAD measurements provide a good indicator of plant-available N in the soil. The method is a quick and cost-effective apparatus to determine when fertiliser is needed without damaging the crop.

4.2.11 Determination of plant biomass

Plant biomass was determined as the total vegetative mass above pot soil level, produced during the growth trial. The harvested biomass was removed with scissors, put in individually marked paper bags and dried in the oven at 80 °C for a minimum of 48 hours, after which the materials were weighed and their dry weights recorded.

4.2.12 Determination of grain and straw yield (barley trials only)

After determining total above-ground biomass in each pot, the barley grain and straw were harvested, separated, oven-dried and weighed as described above.

4.2.13 Statistics

Biomass analysis in all three trials, as well as grain yield, straw residue and tiller numbers in both barley trials, were analysed using a univariate ANOVA design (SPSS v18.0, IBM UK Ltd, Portsmouth, UK) and post-hoc Tukey (HSD) tests to establish the mean standard error of difference between treatments. SigmaPlot v10.0 (Systat Software, San Jose, CA) was used to generate graphs.

4.3 Results

4.3.1 Grass trial

During seed formation, available nutrients are translocated to the top of the tillers to give the seeds the strongest possible start, after which the parent plant dies off (Dorrington-Williams, 1957). Hence top leaf SPAD index values peak just before the grass matures. The NPK grass treatment (Plate 4.1) shows clear signs of necrosis in the older leaves, as nutrients are translocated to the younger shoots (which are not chlorotic) and the plants have not begun to produce tillers. This suggests nutrients were becoming limited due to uptake and leaching after 19 weeks, but the NPK amended grasses were not as stressed as those in the woodchip amendments. The 3 year old woodchip treatments (Plates 4.2 and 4.3) produced less dense swards than the NPK treatment and reached maturity before the trial concluded - see Figure 4.1. These responses indicate a more rapid depletion of available nutrients.

Plate 4.1: Grass trial: Grass in topsoil + NPK (week 19)

Plate 4.2: Grass trial: Grass in topsoil + Pontbren's 3 yr. old compost (week 19)

Plate 4.3: Grass trial: Grass in topsoil + Glynllifon's 3 yr. old compost (week 19)

Plate 4.4: Grass trial – Grass in topsoil + ADAS C55 (week 19)

Plate 4.5: Grass trial – Grass in topsoil only (week 19)

Early sward density in the one-year-old ADAS cattle 55 % woodchip treatments was sparse (Plate 4.4), indicating low germination rate. The grass that did emerge was frail and matured quickly. This growth pattern suggests strong competition for limited nutrients right from the start of the trial. Nevertheless, sward density and growth in the ADAS cattle 55 % woodchip treatments was greater than in the topsoil only control treatment (Plate 4.5), suggesting the amendment had a positive net effect.

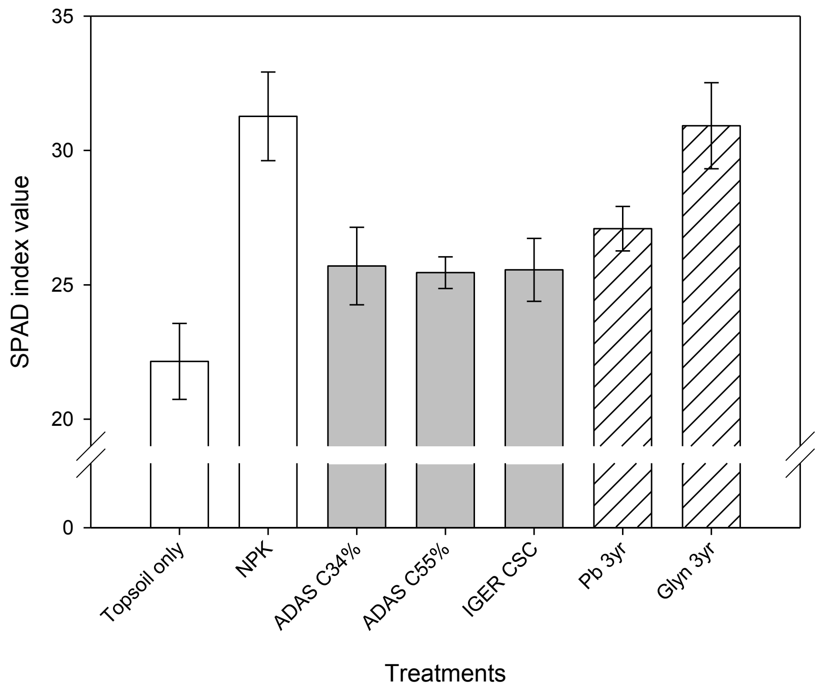

***Figure 4.1**: Grass trial foliar SPAD readings taken at week 19. Control treatments (white bars); 1-year-old cattle woodchip-manure compost (grey bars); independent 3 year old woodchip-manure compost (hashed bars). Error bars represent ± 1 se.*

Table 4.8: Effect of different compost and fertiliser treatments on above-ground grass biomass yield at harvested on 14th April 2008 after 20 weeks. Values represent means ± 1 se. Significant differences between treatments ($p < 0.05$) are denoted by superscript letters.

Treatment	Biomass (g pot^{-1})
Topsoil	1.19 ± 0.10^{a}
NPK	2.79 ± 0.32^{ab}
ADAS C34	1.78 ± 0.50^{ab}
ADAS C55	2.19 ± 0.81^{ab}
IGER CSC	2.26 ± 0.67^{ab}
Pb3	3.11 ± 0.56^{ab}
Glyn3	3.97 ± 0.54^{b}

Biomass yield data in Table 4.8 shows the soil-only control treatment produced significantly less biomass than the Glyn3 treatment. However, notably, there was no significance, and thus agronomic value, between the soil-only and 1-year woodchip amendments. Although biomass was marginally greater in the amended treatments, this could equally be attributed to the woodchip's aeration and water regulating properties (drainage and storage), as opposed to nutrient status. Nevertheless, the results of the grass trial are generally in line with expectations, showing greater above-ground biomass in the amended treatments than the soil-only. This dispels concerns that soil available N would become immobilized owing to the inclusion of C rich material with very low available N. Barker (2001) found leaf and yard waste composts limited growth due to N deficiencies, but also found that N-rich, mature composts provided a good media for promoting turf grass growth. Biomass production in the 3 year old woodchip amendments was encouraging, particularly in comparison to the NPK treatment. I hypothesize that the growth advantage in both of the 3 year old woodchip treatments was enhanced (and possibly determined in Glyn3) by the amendment's physical properties, which promoted soil aeration in the clay rich soil that had a poor structure when wet. Overall, the statistical results of this trial were rather inconclusive, and it is unfortunate that nutrient data for Glyn3 was not available. However, Table 4.3 shows that even after 3 years composting, Pontbren's available N (AN) accounted for only 0.31 % of total N (TN). This compares to a mean AN content of 0.33 % of TN in the 1 year old compost amendments, suggesting that even after 3 years the Pontbren compost was not fully matured. However, the older woodchip amendments did produce the most plant biomass; it is, therefore, concluded that mature woodchip-manure compost has the potential to be a suitable and valuable fertiliser.

4.3.2 B100 barley trial

In all treatments except ADAS SS, SPAD index values peaked in week 8 as the barley went to seed, after which the parent plants gradually died off. The relative persistence of top leaf chlorophyll in the straw-based treatments (see Figure 4.2) indicates sufficient nutrients were available throughout the trial, in comparison to barley grown in the NPK amended topsoil, which produced the highest SPAD value of all the treatments in week 8, but one of the lowest by week 10. Bar-Tal et al. (2004) showed that organic compost, when applied to land consistently over a number of years, generates a build-up of soil nutrients, so gradually less compost is needed to maintain soil fertility. There was a marked textural (maturity) difference between the Pontbren compost - which had a rich loamy texture with no remaining woodchip - and the water-logged Glynllifon compost that contained many sizable, intact woodchips. This contrast between the two 3 year old composts is evident in biomass and grain yields shown in Figures 4.3 and 4.5, which illustrates the importance of good compost management and the potential agronomic value of woodchip-manure. It was anticipated the B10 results would be less contrasting in this regard, hence the decision to carry out this trial at amplified application rates.

As expected, the fine (< 8 mm) fractions of IGER's 1 year old amendments produced greater biomass and grain yield than their corresponding large (> 8 mm) fractions (see Figure 4.3). However, sieving the compost every summer solely to extract the fine material for fertilizer is considered uneconomic, as after 7 months composting, the fine fraction only represented 14 % of the total composted bedding. Therefore, a farmer would initially need 7,143 tons of unsieved compost to extract enough fine material to cover 10 hectares at 100 t/ha. Even if the bedding were deployed economically, that quantity of woodchip would be sufficient to house 14,617 cattle or 63,724 sheep, so by necessity, the farm would have many hundreds of hectares. Furthermore, this application rate would cover the ground 1.75 cm deep. In addition, by applying the compost by weight, rather than by percentage N, resulted in the drier straw amendments having a nutritional advantage over the woodchip-based amendments. However, sieving the immature woodchip bedding-compost each summer could prove to be commercially advantageous on a number of levels: firstly, by sieving the material straight after the compost has achieved thermophilic temperatures, farmers would limit the risk of pathogen re-inoculation by removing the most nutritious compost material, and, in so doing, restricting any excess degradation of the woodchips, concomitantly extending the woodchip's viability as a bedding material. In addition, removing the manure fraction from the sanitized woodchips before storage during the summer would enhance airflow through the pile, ensuring a lower moisture content in the recycled woodchip and therefore producing more efficient bedding the following winter.

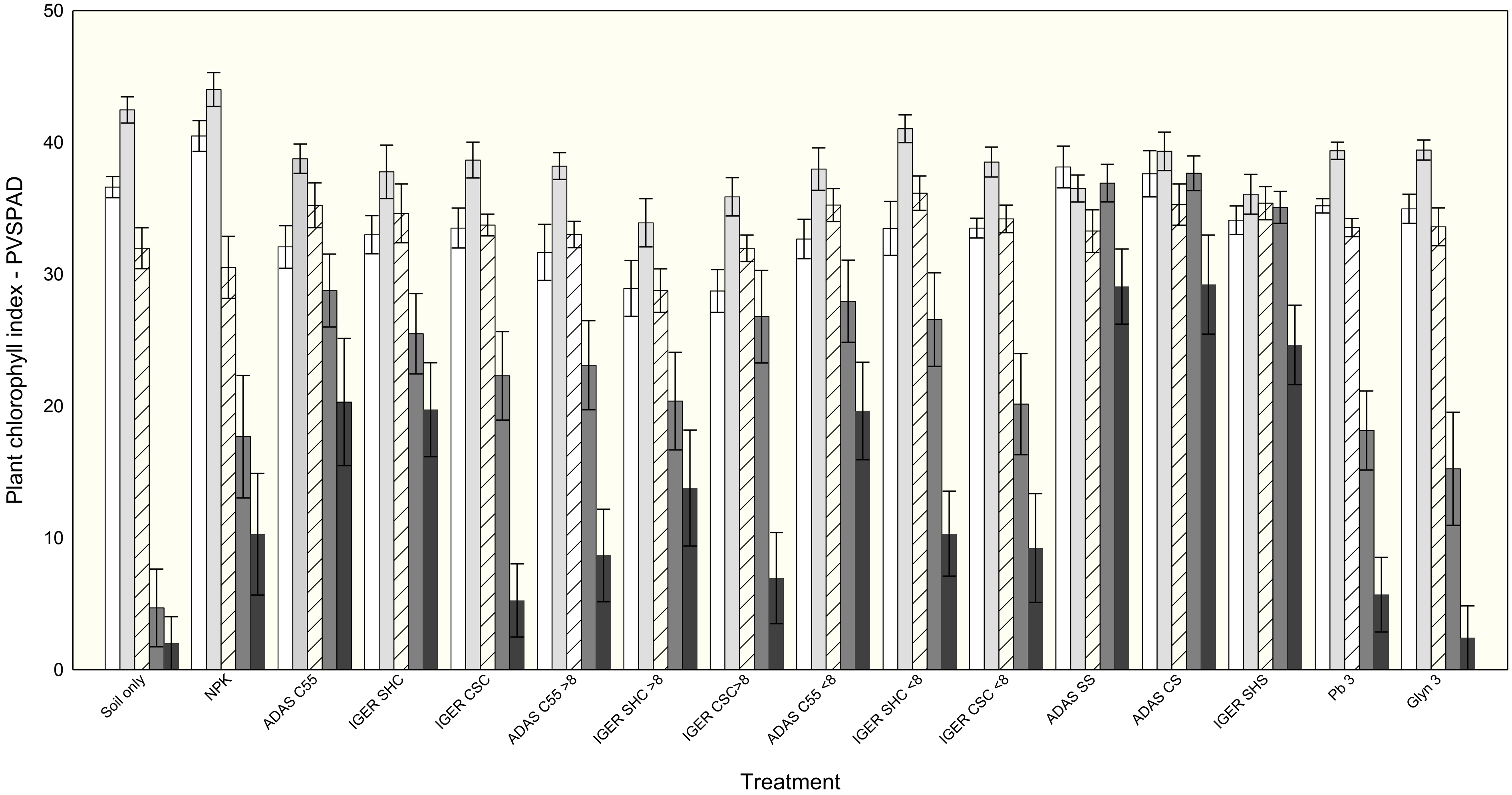

Figure 4.2: *B100 Optic barley trial, top leaf chlorophyll index (SPAD) at week 6 (white bars); week 8 (light grey bars); week 10 (hashed bars); week 12 (mid grey bars) and week 14 (dark grey bars). Compost applied at 100 t/ha in treatments 3 – 16 and NPK 221-84-116 kg/ha in treatment 2). Error bars represent ±1 se.*

Plate 4.6: B100 Trial: *Optic* barley in topsoil + ADAS CS (week 12)

Plate 4.7: B100 Trial: *Optic* barley in topsoil + IGER CSC (week 12)

Plates 4.6 and 4.7 contrast barley growth and fecundity between the ADAS cattle fed silage on straw, and the IGER cattle fed silage on woodchip treatments after 12 weeks.

Plate 4.8: B100 Trial: *Optic* barley in topsoil + Pontbren's 3 yr. old (week 12)

Plate 4.9: B100 Trial: *Optic* barley in topsoil + Glynllifon's 3 yr. old (week 12)

Plates 4.8 and 4.9 illustrate the difference in productivity between the two 3 year old woodchip-manure compost amendments. Pontbren's rich loamy compost had no intact woodchips, whereas Glynllifon's water logged, immature amendment still contained large quantities of sizable woodchips.

Plate 4.10: B100 Trial: *Optic* barley in topsoil + IGER SHC < 8mm (week 15)

Plate 4.11: B100 Trial: *Optic* barley in topsoil + IGER SHC > 8mm (week 15)

Plates 4.10 and 4.11, and 4.12 and 4.13, illustrate the productivity of IGER's SHC and CSC small (< 8 mm) and large (> 8 mm) fractions. The small fractions contained mostly degraded manure and waste feed with a few wood particles, whereas the large fraction was made up of mostly intact large woodchips. However, the cost/benefit of sieving year-old woodchip-manure compost at farm-scale proved uneconomic.

Plate 4.12: B100 Trial: *Optic* barley in topsoil + IGER CSC < 8mm (week 15)

Plate 4.13: B100 Trial: *Optic* barley in topsoil + IGER CSC > 8mm (week 15)

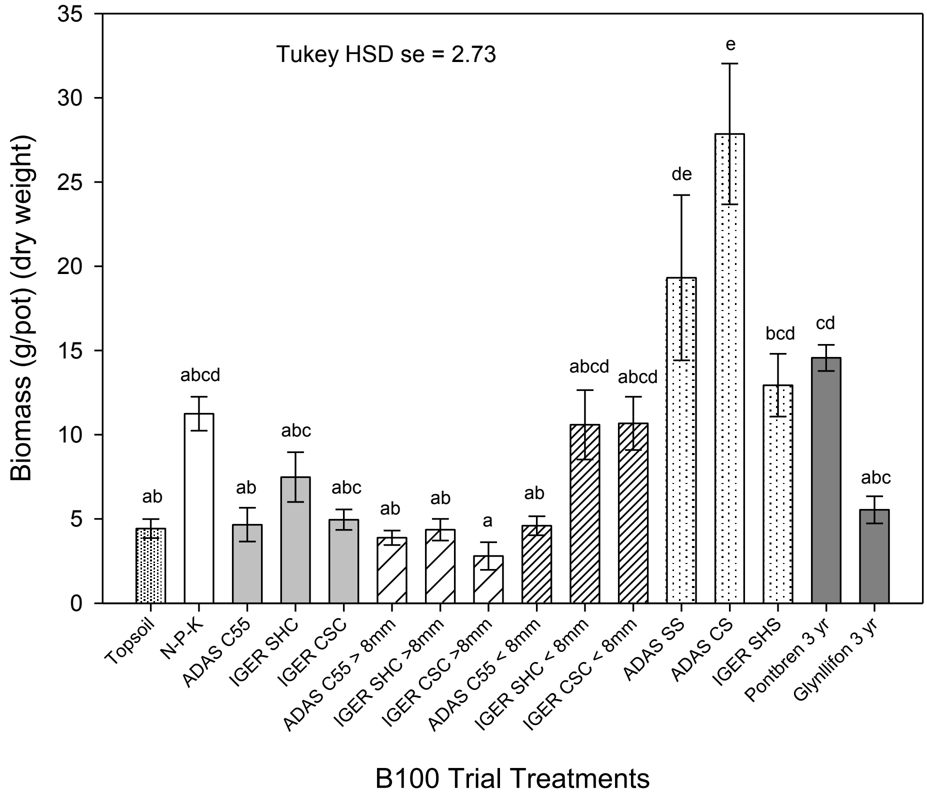

Figure 4.3: *Above-ground plant biomass (g pot^{-1}) dry weight in B100 Optic barley trial including Tukey HSD standard error of the difference (harvest date 13th November 2007). Bar patternation represent amendment groups, left to right; controls (intensely dotted and white bars); 1 yr. old composts (mid-grey bars); large (>8 mm) 1yr. old fractions (wide hashed bars); fine (<8 mm) 1 yr. old fractions (narrow hashed bars); straw composts (dotted bars) and 3 yr. old composts (dark grey bars). Error bars represent ±1 se. Different letters indicate significant differences between treatments at p < 0.05.*

The B100 trial biomass results (Figure 4.3) show ADAS CS produced greater biomass than all others treatments ($p<0.01$), except ADAS SS ($p>0.05$). In contrast, all three large (>8 mm) fraction amendments were the least agronomic, producing significantly less biomass than Pontbren ($p<0.05$) and both ADAS straw amendments ($p<0.001$) and even the zero-addition control treatment, although not significantly ($p>0.05$). Dumont et al. (2010) discuss this occurrence in relation to N uptake in grass grown in spent timber residues, and suggest N immobilization may be the causal factor, although they do not rule out the basic lack of available N in the amendment. Likewise, both these factors are considered to have strongly influenced the results of the present study.

Analysis of treatment groups (groups are defined in Table 4.4), shows straw amendments contain the most agronomic value ($p<0.01$) compared to all other groups except the NPK treatment (p>0.05), but the actual result was (p<0.055). On weight-based application rates, the straw composts have a nutritional advantage over woodchips, highlighting the real agronomic value of the 3 year old Pontbren treatment and the benefit of good compost management, which is in contrast to the biomass yield from the Glynllifon 3-year old (unmanaged) compost.

Table 4.9: Total pots, plants and tillers treatment^{-1}; average number of tillers plant^{-1} incl. ± 1 se.

B100 treatments	Pots	Plants	Tillers	Tillers plant^{-1}
Topsoil	4	14	15	1.08 ± 0.08
N-P-K (221-84-116 kg/ha^{-1})	4	16	42	2.63 ± 0.22
ADAS C55	4	14	29	2.08 ± 0.08
IGER SHC	4	13	33	2.65 ± 0.38
IGER CSC	4	14	26	1.90 ± 0.18
ADAS C55 > 8mm	4	14	26	1.88 ± 0.18
IGER SHC > 8mm	4	16	29	1.81 ± 0.26
IGER CSC > 8mm	4	12	18	1.54 ± 0.21
ADAS C55 < 8mm	4	16	28	1.75 ± 0.14
IGER SHC < 8mm	4	15	44	2.94 ± 0.43
IGER CSC < 8mm	4	15	39	2.65 ± 0.39
ADAS SS	4	13	54	4.00 ± 0.54
ADAS CS	4	14	81	5.85 ± 0.74
IGER SHS	4	14	41	3.06 ± 0.41
Pontbren 3 yr.	4	14	49	3.65 ± 0.59
Glynllifon 3 yr.	4	15	25	1.67 ± 0.26

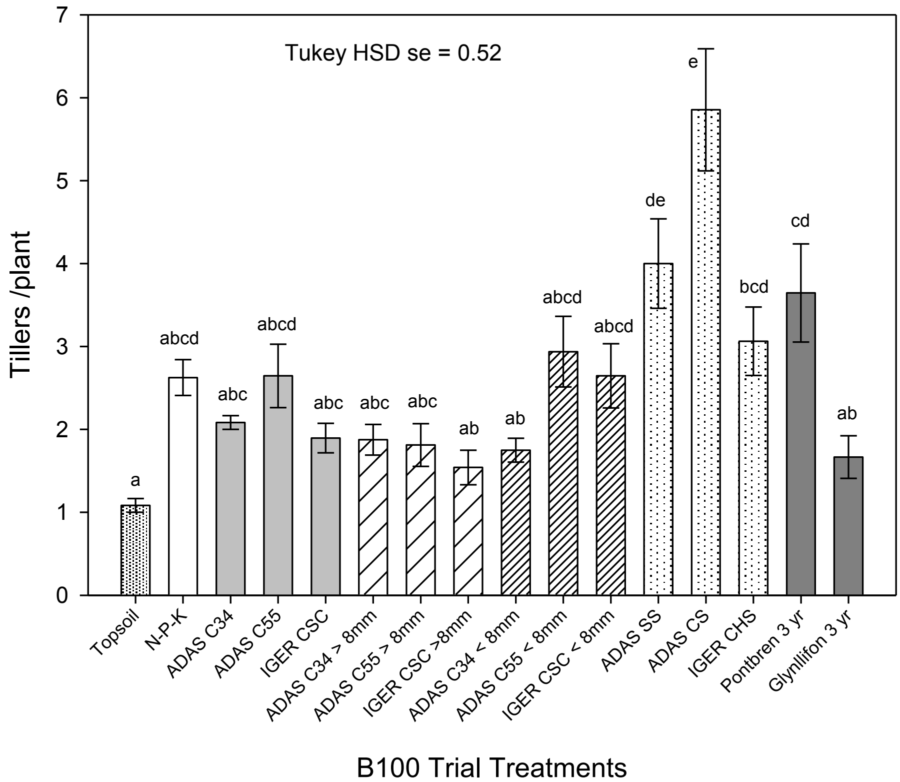

Figure 4.4: *Number of tillers plant^{-1} (counted on 13th November 2007) in the B100 Optic barley trial including Tukey HSD. Bar patternation represent amendment groups, left to right:; controls (intensely dotted and white bars); 1 yr. old composts (mid-grey bars); large (>8 mm) 1yr. old fractions (wide hashed bars); fine (<8 mm) 1yr. old fractions (narrow hashed bars); straw composts (dotted bars) and 3 yr. old composts (dark grey bars). Error bars represent ±1 se. Different letters indicate significant differences between treatments at $p < 0.05$.*

Tillering m^{-2} is a quick, non-intrusive method of assessing the nitrogen content in crops. DEFRA (2010) estimate that 500 shoots m^{-2} is indicative of crops containing 5 kg N ha^{-1} in late autumn and 15 kg N ha^{-1} in early spring. As the pot trials were conducted under controlled climatic conditions, Table 4.10 shows the estimated barley N content ha^{-1} derived from DEFRA's early spring figures.

Table 4.10: estimated (*in italics*) barley N content kg ha^{-1} in the B100 trial treatment groups, based on tillers m^{2} in early spring conditions (DEFRA, 2010).

Treatment Groups	Tillers m^{-2}	Barley kg N ha^{-1}
Topsoil	*26*	*0.79*
NPK	*73*	*2.20*
Parent compost	*51*	*1.54*
Large fraction	*42*	*1.27*
Small fraction	*65*	*1.94*
Straw	*102*	*3.07*
3 year old	*65*	*1.94*

In comparison to other studies (Le Gouis, 1999; Benke, 2010) these estimates are very low. This may be caused by an anomaly in scaling up the data i.e. 70 pots m^{-2}, leaching, or factors relating to pot scale growth conditions such as pot volume limiting rhizosphere development, and/or the C:N ratio of the amendments (Qian and Schoenau, 2002). Table 4.9 shows that germination rate was between 81 % (plants n=13) in 2 treatments and 100% in 3 treatments. Nevertheless, Figure 4.4 shows tillering plant^{-1} is strongly correlated to biomass, although, notably, plants grown in the large (>8 mm) fraction amendments produced 2 tillers plant^{-1} compared to 1 tiller plant^{-1} in the soil-only control, suggesting there was greater nutrient availability in the large fraction amendments than in the soil-only during the early weeks of the trial when shoots were forming, but that available nutrient levels in (>8 mm) dropped below those in soil-only, as the trial progressed, hence the biomass results seen in Figure 4.3.

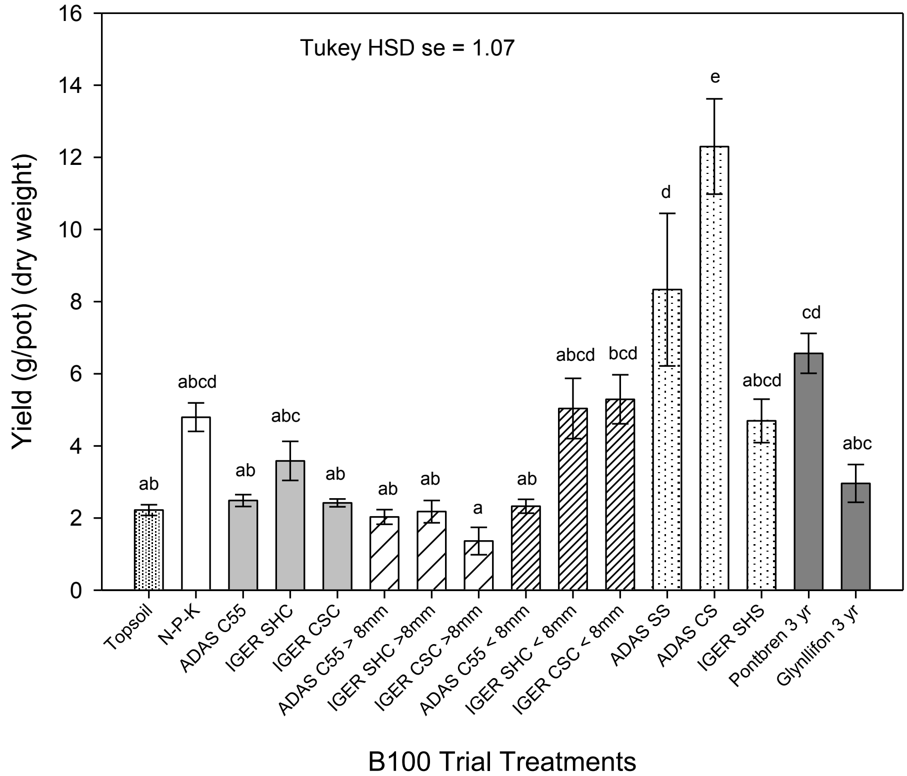

Figure 4.5: *Grain yield (g pot^{-1}) dry weight in the B100 Optic barley trial including Tukey HSD standard error of the difference (harvest date 13th November 2007). Bar patternation represent amendment groups, left to right: controls (intensely dotted and white bars); 1 yr. old composts (mid-grey bars); large (>8 mm) 1 yr. old fractions (wide hashed bars); fine (<8 mm) 1 yr. old fractions (narrow hashed bars); straw composts (dotted bars) and 3 yr. old composts (dark grey bars). Error bars represent ±1 se. Different letters indicate significant differences between treatments at p < 0.05.*

Grain yields are closely correlated to biomass, ADAS CS yielded significantly more grain than all other treatments ($p<0.001$) and ADAS SS ($p<0.05$). Both IGER's small (<8 mm) fractions produced greater ($p>0.05$) yields than all the 1 year old amendments and inorganic NPK. Yield from the Pb 3 year old amendment was greater ($p >0.05$) than from all 1 year old woodchip composts and significantly ($p <0.05$) than all 3 large fraction 1 year old amendments.

Again, the three large (> 8 mm) fraction composts yielded less grain than all the other treatments, including the soil-only control, but statistical differences are limited by treatment to Pontbren ($p<0.05$) and both ADAS straw amendments ($p<0.001$) and - as a group - only straw ($p<0.001$). Interestingly, though not significantly, sheep on woodchips result in greater productivity than cattle on woodchips, whereas the opposite is true in the straw amendments. This observation is considered the result of B:M interactions, discussed in Chapter 3 - in particular, woodchip's capacity to absorb the small, discrete urine volumes that sheep produce compared to cattle.

Analysis of grain yield by treatment group (defined in Table 4.4), shows exactly the same results as biomass production – higher yields from straw than all other groups ($p<0.001$), except the 3 year old composts ($p<0.01$) and the NPK treatment ($p>0.05$).

Similarly, straw residues (data not shown) determined as biomass - grain yield was significantly ($p<0.001$) greater from the straw compost amendments than from all 3 groups of 1-year old woodchip amendments. There were however, no statistical differences, at any measure, between the 1 year old parent compost amendments and their large and small fractions.

Table 4.11: two estimates (italics) of percentage N uptake in B100 trial *Optic* barley based on biomass N content of 11.8 mg N g^{-1} DM (IOTA fresh weight data was adjusted to account for an estimated 20 % moisture content). Column (2nd from right), shows estimated crop uptake (%) of initial DIN content and column (far right) shows estimated crop uptake (%) of initial DIN after 20 % mineralization of initial TN content. *Italics* denote estimated data, see footnotes for data sources.

B100 Trial Treatments	Biomass g pot^{-1}	* Biomass mg N pot^{-1}	DIN ** mg pot^{-1}	% Uptake of initial DIN	% Uptake of initial DIN*** +20% mineralisation of TN
Topsoil	4.43	*52.4*	*17.7*	*296*	*94.9*
NPK	11.2	*122*	*334*	*36.5*	*28.1*
ADAS C55	4.66	*57.0*	*15.0*	*380*	*17.6*
IGER SHC	7.49	*86.3*	*54.5*	*158*	*23.5*
IGER CSC	4.96	*57.7*	*17.3*	*333*	*22.7*
ADAS C55 >8	3.88	*47.0*	*14.3*	*329*	*18.6*
IGER SHC >8	4.36	*51.4*	*24.5*	*210*	*19.3*
IGER CSC >8	2.80	*32.5*	*17.0*	*192*	*13.5*
ADAS C55 <8	4.60	*54.7*	*17.4*	*314*	*9.75*
IGER SHC <8	10.6	*122*	*37.6*	*323*	*19.6*
IGER CSC <8	10.7	*125*	*21.6*	*580*	*28.8*
ADAS SS	19.3	*211*	*227*	*92.6*	*24.0*
ADAS CS	27.9	*307*	*266*	*115*	*27.9*
IGER SHS	12.9	*129*	*256*	*50.5*	*12.2*
Pb3	14.6	*162*	*27.7*	*587*	*15.3*
Glyn3	5.54	*67.9*	ND	ND	ND

* Biomass N content 11.8 mg N g-1 DM (adjusted for estimated 20% MC) derived from IOTA (2012)

** Soil TN and DIN were analysed by Lucas, published in Lucas and Jones, (2009)

*** Includes 20 % mineralisation of TN during growth trial, (Hadas and Portnoy, 1994)

Table 4.11 attempts to estimate % N uptake in B100 trial treatments based on fresh weight crop N content data (IOTA, 2012), then adjusted for 20 % (whole crop) moisture content (11.8 mg N g^{-1} DM). Further, estimates are given for % N uptake (including initial DIN content) based on 20 % of

TN in the potting medium, becoming available via mineralization during the growth trial. Hadas and Portnoy (1994) reported that between 11 and 29 % of TN was mineralized in 4 composted cattle manures incubated in soil over a 32 week period at 30° C and 60 % water-holding capacity.

4.3.3 B10 barley trial

SPAD values in the B10 trial (shown in Figure 4.6) peaked in week 10, as opposed to week 8 in the B100 trial, and chlorophyll levels remained high for longer across all treatments, although index readings were lower than in the B100 trial.

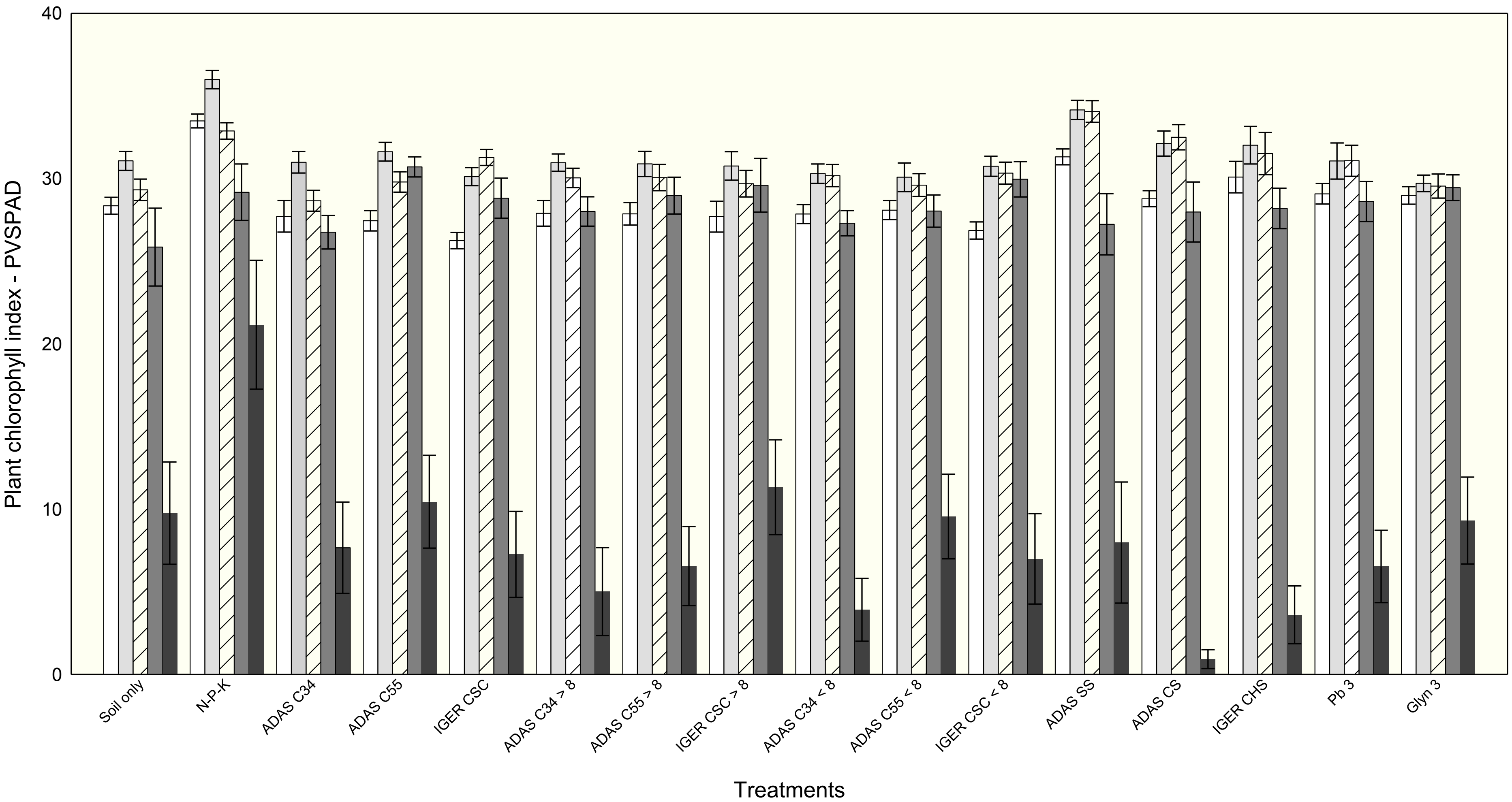

Figure 4.6: *B10 Optic barley trial, top leaf chlorophyll index (SPAD) at week 8 (white bars); week 10 (light grey bars); week 12 (hashed bars); week 14 (mid grey bars) and week 16 (dark grey bars). Compost applied at 10 t/ha in treatments 3 – 16 and NPK 150-57-79 kg/ha in treatment 2). Error bars represent ±1 se.*

Plate 4.14: B10 Trial: *Optic* barley in topsoil + Pontbren's 3 yr. (week 12)

Plate 4.15: B10 Trial: *Optic* barley in topsoil + Glynllifon's 3 yr. (week 12)

Plate 4.16: B10 Trial: *Optic* barley in topsoil + ADAS C34 > 8mm (week 12)

Plate 4.17: B10 Trial: *Optic* barley in topsoil + ADAS C34 < 8mm (week 12)

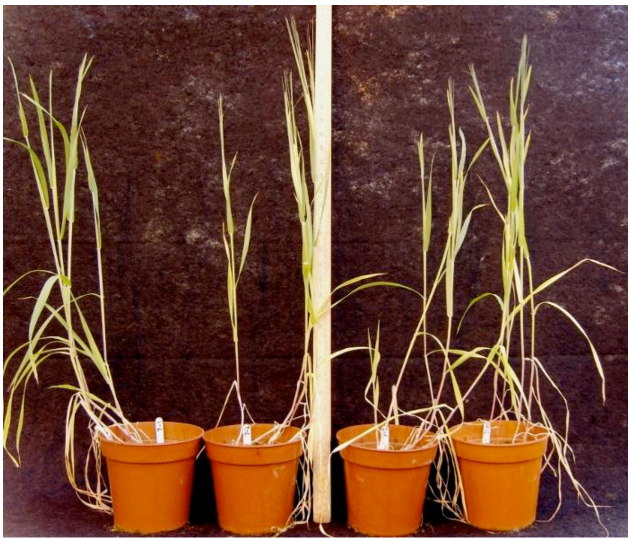

Plate 4.18: B10 Trial: *Optic* barley in topsoil + ADAS C55 > 8mm (week 12)

Plate 4.19: B10 Trial: *Optic* barley in topsoil + ADAS C55 < 8mm (week 12)

In contrast to the B100 plates, there is a striking similarity between all six treatments featured in the B10 plates above. All plants express N deficient chlorosis in the middle leaves and necrosis in the lower leaves at week 12.

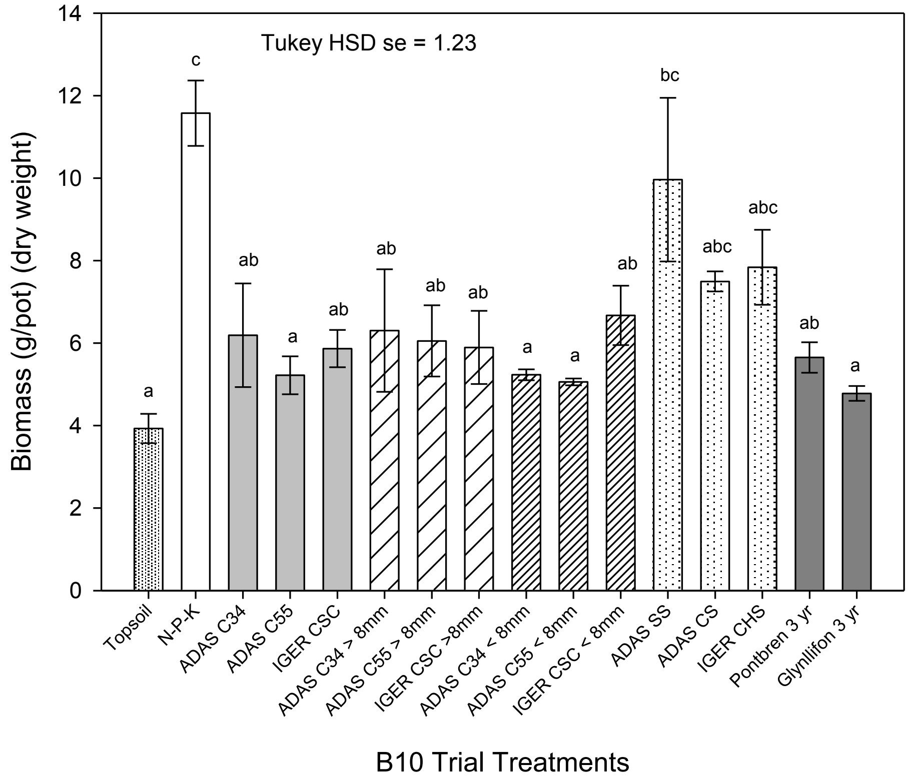

Figure 4.7: *Above-ground plant biomass (g pot^{-1}) dry weight in B10 Optic barley trial including Tukey HSD standard error of the difference (harvest date 28th March 2008). Bar patternation represent amendment groups, from left to right; controls (intensely dotted and white bars); 1 yr. old composts (mid-grey bars); large (>8 mm) 1yr. old fractions (wide hashed bars); fine (<8 mm) 1 yr. old fractions (narrow hashed bars); straw composts (dotted bars) and 3 yr. old composts (dark grey bars). Error bars represent ±1 se. Different letters indicate significant differences between treatments at* $p < 0.05$.

Biomass yield from the large and small woodchip fractions of both ADAS C34 and C55 composts seem counter-intuitive (see Figure 4.7), as both ADAS's large fraction amendments produced greater biomass than their respective small fractions. This trial's application rate is determined to achieve optimal results from nutrient-rich organic compost and, as shown in Chapter 3, the project's woodchip composts are N deficient compared to the straw compost. So it is suggested the agronomic advantage in the ADAS large fractions is due to the intact woodchips acting as a soil bulking agent, regulating soil moisture and providing aeration. Although, in comparison, the biomass produced in each of IGER's three CSC derived amendments are in line with expectations.

Therefore, it is suggested that this paradox, specific to the ADAS amendments, relates to the use of a scraped area within the ADAS cattle pens during the bedding phase, but further research would be needed to validate this point. However, contrary to the grass trial results, the ADAS C34 amendment yielded greater barley biomass ($p > 0.05$) than the ADAS C55, indicating the initially drier C34 woodchip bedding amendment retained greater amounts of available nutrients during the B10 trial. This supports the hypothesis that woodchips with lower moisture content have a greater absorbency capacity as a bedding material. Although, this effect may be more conclusively proven in growth trials using higher compost application rates than 10 t ha^{-1}. Pb3 (Plate 4.14) produced taller and structurally stronger plants than the corresponding Glyn3 compost (Plate 4.15), but produced similar biomass and grain yields than the 1-year old woodchip amendments. This is considered a response to the surprisingly low AN content in the 'well-managed' Pb3 compost (see Table 4.7) and critical to understanding the timescale that woodchips remain viable as a bedding material (lifespan) and compost maturation.

Analysis of differences between treatment groups (defined in Table 4.6) supports the pattern described between individual amendments: NPK produced significantly greater biomass than all other groups, ($p<0.001$), and straw ($p<0.05$). Straw amendments produced greater biomass than soil-only, parent composts, small fractions and 3 year old composts ($p<0.01$) and large fractions ($p<0.05$).

Table 4.12: total number of pots, plants and tillers treatment^{-1}; average number of tillers plant^{-1} inc. ± 1 se.

B10 treatments	Pots #	Plants #	Tillers #	Tillers plant^{-1}
Topsoil	4	16	17	1.06 ± 0.06
N-P-K (150-56-79 kg/ha^{-1})	4	16	29	1.81 ± 0.06
ADAS C34	4	16	18	1.13 ± 0.13
ADAS C55	4	16	17	1.06 ± 0.06
IGER CSC	4	16	18	1.13 ± 0.13
ADAS C34 > 8mm	4	16	18	1.13 ± 0.13
ADAS C55 > 8mm	4	16	20	1.25 ± 0.18
IGER CSC >8mm	4	16	18	1.13 ± 0.13
ADAS C34 < 8mm	4	17	17	1.00 ± 0.00
ADAS C55 < 8mm	4	12	13	1.08 ± 0.06
IGER CSC < 8mm	4	16	16	1.00 ± 0.06
ADAS SS	4	12	18	1.50 ± 0.24
ADAS CS	4	16	16	1.00 ± 0.06
IGER CHS	4	12	16	1.33 ± 0.12
Pontbren 3 yr.	4	16	19	1.19 ± 0.06
Glynllifon 3 yr.	4	12	14	1.17 ± 0.10

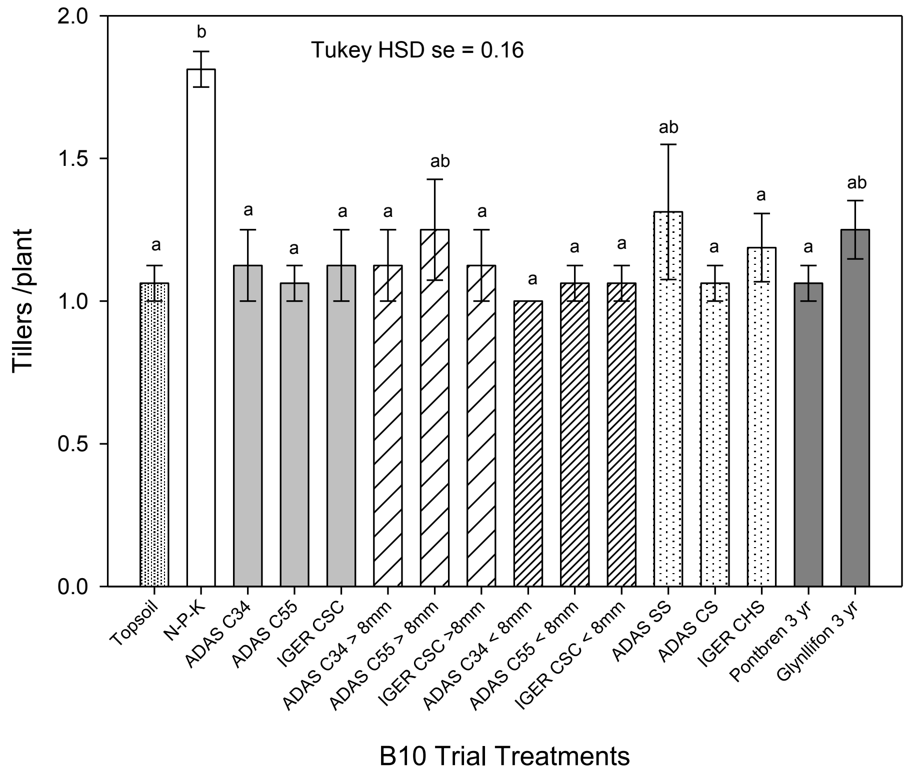

Figure 4.8: *Number of tillers plant^{-1} in the B10 Optic barley trial including Tukey HSD standard error of the difference (counted on 28th March 2008). Bar patternation represent amendment groups, left to right; controls (intensely dotted and white bars); 1 yr. old composts (mid-grey bars); large (>8 mm) 1 yr. old fractions (wide hashed bars); fine (<8 mm) 1 yr. old fractions (narrow hashed bars); straw composts (dotted bars) and 3 yr. old composts (dark grey bars). Error bars represent ±1 se. Different letters indicate significant differences between treatments at $p < 0.05$.*

The lack of tillering plant^{-1} in the B10 trial (Table 4.12 and Figure 4.8) is considered to result from the low compost application rate and thus limited amounts of available nutrients. In addition, seasonal effects, particularly temperature, even under greenhouse conditions, cannot be ruled out, and if this was the case, then watering the barley on a daily basis may have negatively influenced growth. This is postulated because the B10 NPK treated barley (Plate 4.20) was not initially nutrient deficient, but produced one less tiller plant^{-1} than the B100 NPK barley, which was grown during spring and summer, and the ADAS and IGER field trial results (see Appendix II) show barley biomass increases sharply at application rates up to 75 – 100 kg N ha^{-1}, but then yields level off at rates >75 kg N ha^{-1} as crop N requirements are met and the excess is wasted.

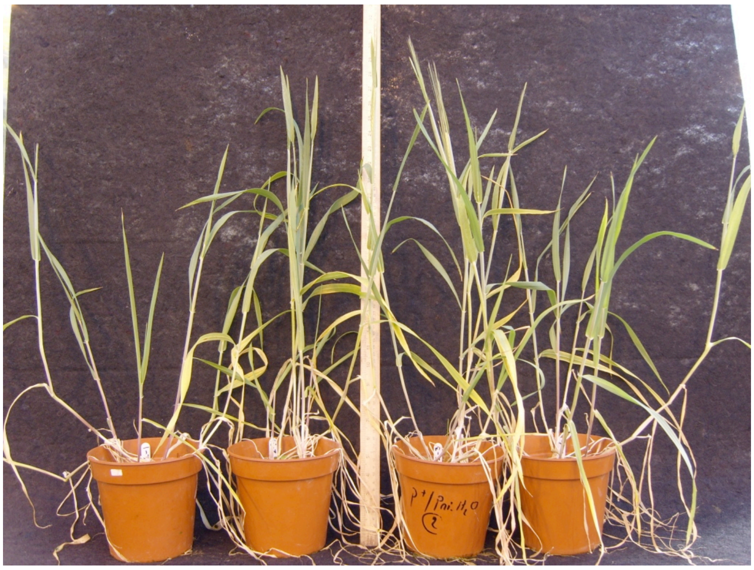

Plate 4.20: B10 Trial: *Optic* barley in topsoil + NPK (week 12)

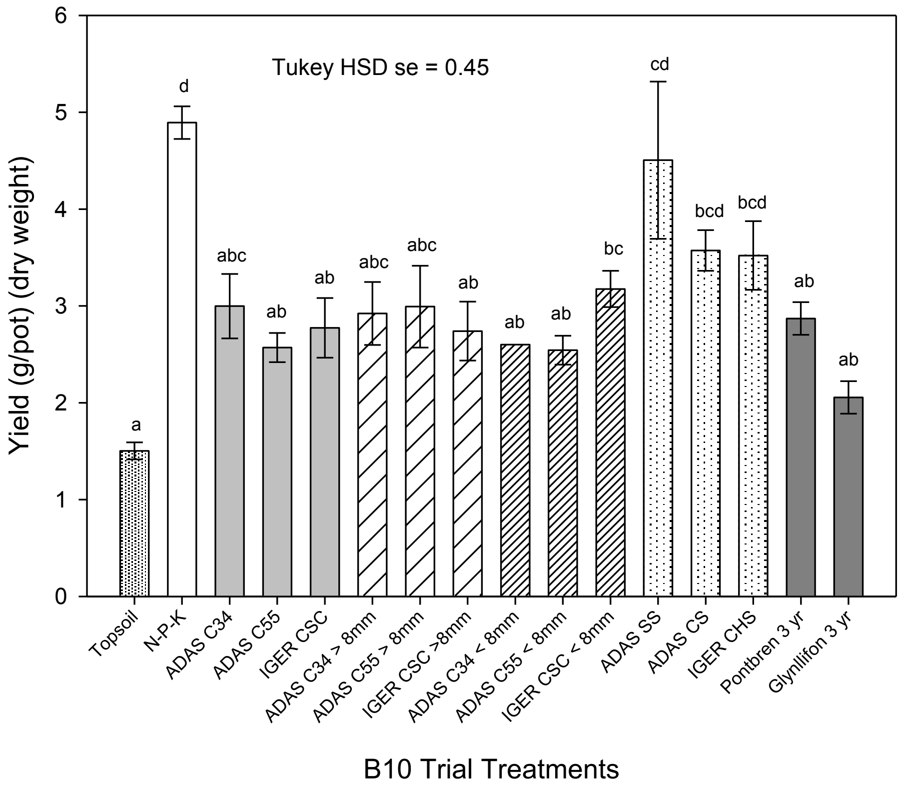

Figure 4.9: *Grain yield (g pot^{-1}) dry weight in the B10 Optic barley trial including Tukey HSD standard error of the difference (harvest date 28th March 2008). Bar patternation represent amendment groups, from left to right; controls (intensely dotted and white bars); 1 yr. old composts (mid-grey bars); large (>8 mm) 1 yr. old fractions (wide hashed bars); fine (<8 mm) 1 yr. old fractions (narrow hashed bars); straw composts (dotted bars) and 3 yr. old composts (dark grey bars). Error bars represent ±1 se. Different letters indicate significant differences between treatments at $p < 0.05$.*

Grain yield in the B10 trial was dominated by the NPK treatment (Plate 4.20), which produced significantly greater quantities than all the woodchip amendments ($p<0.05$) and the soil-only control ($p<0.001$), but none of the straw treatments (see Figure 4.9). ADAS SS produced significantly more grain than most 1 year old woodchip derivatives ($p<0.05$), with the exception of ADAS C34; both ADAS C34 and C55 (>8 mm) and IGER CSC (<8 mm). Agronomic differences between the 1 and 3 year old woodchip amendments were not significant at rates of 10 t ha^{-1}. However, even at this lower application rate, there are still notable differences between the two aged amendment performances, reaffirming the benefits of good compost management.

Overall, these results show that at pot scale, an equivalent of 10 t ha^{-1} of low nutrient woodchip compost is beneath the rate needed to determine significant variations in plant growth between woodchip derived amendments. Although the weight-based advantage of nutrient rich, straw compost were apparent. Further trials, based on percentage N applications rates, are needed to clarify these results.

Interestingly, analysis of grain yield between groups shows greater variation than observed in the biomass-grouped analysis. NPK grain yield is again significantly different from all other groups ($p<0.001$) except straw ($p>0.05$). Grain yield is significantly greater in straw amendments (by group) than the soil-only and 3 year old woodchip compost ($p<0.001$) and the three groups of 1-year old woodchip composts ($p<0.01$). In addition, the soil-only treatment yielded significantly less grain than NPK and straw compost ($p<0.001$); large fraction ($p<0.01$); whole and small fraction groups ($p<0.05$); but not statistically less than the 3-year old woodchip compost ($p>0.05$) - although sample size (n=2), compared to (n=3) in other groups may have biased the result.

Of the three analyses - biomass, grain and straw yield - straw yields (data not shown) vary the least with the results similar to those for biomass, except that the quantity of straw harvested from the NPK was not significantly greater than the straw produced in the small fraction of IGER's CSC ($p>0.05$).

4.4 Discussion

The grass trial set out to establish the agronomic value of 3 year old woodchip bedding-compost in comparison to 1 year old woodchip-manure compost. It may be in the farmer's interest to limit the amount of decomposition between housing periods to extend the life of the woodchip's usefulness as a bedding material. However, as an absolute minimum, the compost must be managed sufficiently well to meet the UK PAS100 pathogen regulation, which requires that the 'compost must reach 65° C for at least 7 days' (WRAP, 2005) before it can be re-used the following season as livestock bedding.

The two barley trials determined that, at farm-scale production volumes, there was no agronomic benefit in sieving the woodchip-manure composts each year to extract the fine fraction. Compost nutrient analyses discussed in Chapter 3 show the project's 1 year old woodchip composts are nutrient deficient, at least at levels necessary to add value as a fertiliser. Of these, available nitrogen appears to be the deficiency most strongly expressed in the barley B10 and B100 trials (Berry, 2010). Furthermore, the B10 results show that the ADAS C34 derivatives, with lower initial moisture content, produced a greater plant biomass than ADAS C55 with higher initial moisture content. This suggests the absorbency potential of initially dryer woodchips becomes transferred in sequestering a greater nutrient load than woodchips with higher initial moisture content. In addition, it is reasonable to assume that efficient composting during the summer months not only sanitizes the compost - a legal requirement for its re-use - but higher composting temperatures increase evaporation, thus producing a more absorbent bedding the following winter and, ultimately, a higher value fertiliser when the woodchips are finally degraded sufficiently to be applied to land.

None of the woodchip-manure compost treatments in the B10 trial matched the productivity of NPK or straw-based compost treatments, due to the nutritional disadvantage with straw. However, the agronomic value of Pontbren's well-managed compost is encouraging, demonstrating woodchip's potential value to Welsh farming in the near future. Although this is a national project, its purpose is to assist individual farmers in making personal decisions when straw bedding prices become uneconomic. The project did not suggest woodchip is the only or the best alternative to straw and fully encouraged individuals to develop innovative, cost-effective solutions for themselves, so long as the materials, and the way they are used, conformed to regulatory waste requirements. However, at a national level, woodchip was considered the most widely available material in Wales, and, to that end, the project aimed to deliver impartial and helpful advice. Following these growth trials, the project recommended:

1. Re-use of the compost-sanitized bedding for consecutive winters, as long as the woodchips remain intact and viable as bedding, before spreading it on the land.
2. There is no agronomic benefit from sieving the woodchip-manure compost for fertiliser each year, although this is surpassed by the economic benefits of extending the woodchip's viability as a bedding material.

The predominant theme to emerge from other growth studies that include woodchip amendments is reduced yields due to microbial immobilization of N. Variations occur dependent on age, species of plants and whether the woodchips are co-composted or mixed with other amendments. However, there are instances where woodchip-induced N immobilization is a benefit. Van Rensburg and Morgenthal (2004) studied the remedial effects of adding small applications (5-15 t/ha) of woodchips to platinum tailings in South Africa, and found them beneficial to the early establishment of vegetation by increasing plant production, basal cover and medium nutrient status (P and K). The study considered that the woodchip additions reduced nitrate contamination through microbial N immobilization, although the authors cautioned that the positive effects on growth may be reversed if the microbial response is prolonged, and suggested that the woodchips are composted first. The obvious relevance of this to Welsh agriculture is in nitrate vulnerable zones where the woodchip compost applied in the autumn could be used to reduce N leaching (Smith et al., 2010).

Organic production systems are often blighted by weed encroachment, resulting in lower yields and, consequently, less competitive prices than conventional equivalents. Law et al. (2006), trialled two commercial techniques for growing organic bell peppers (flat, bare ground versus black, polythene-covered raised beds), both treatments were tested under five weed suppressant regimes (straw, compost, woodchips, undersown clover and an organic herbicide) to assess pepper yield and weed control efficacy. The trials concluded that organic bell pepper yields, similar to those gained from inorganic production, can be achieved by combining the polythene-covered raised bed system with mid-season, inter-row applications of woodchip mulch. Although organic horticultural production is limited in Wales, if UK consumer demand for local produce continues to increase, then its relevance would be enhanced. However, the fertility value of immature woodchip compared to other amendments, consistently resulted in low or negative productivity, especially under pre-emergent and young vegetation, including trees (Chong and Lumis, 2000; Venner et al., 2011), crops (Termine et al., 1987; Miyasaka et al., 2001; Soumare et al., 2002; Helgason et al., 2007; Smiciklas et al., 2008; Pill and Goldberger, 2009), grasses (Sullivan et al., 1998; Barker, 2001) and ornamental flowers (Bugbee, 2002; Jayasinghe et al., 2010).

Venner et al. (2011) found similar issues in woodchip's performance as an organic-waste-derived substrate to those found in this project, albeit under paper birch (*Betula papyrifera*) seedlings, demonstrating the spectrum of species inhibited by the inclusion of immature woodchip in the growing media. The study also reported that small woodchips (< 10 mm) caused waterlogging, and so recommends the use of large chunks, applied as an incorporated amendment, not surface mulch, to give soil structure and break-up the focus of N immobilization in the soil. Conversely, TerAvest et al. (2010), reported that N enriched woodchip compost, applied to young *in situ* orchard apple trees (*Malus domestica Borkh*), 18 months prior to sampling, had beneficial effects on growth compared to ground cultivation or legume cover crops. Translocation of N to growth zones in spring and perennial wood N reserves in summer was greatest in trees treated with the enriched woodchip compost. Woodchip compost enrichment with inorganic fertiliser in this instance, but also with biosolids (Barker, 2001; Bugbee, 2002; Pill and Goldberger, 2009), allows the pre-established vegetation to benefit from the positive soil structural advantages, while mitigating the limiting effects of immobilization. These findings reflect very positively on the recommendation that woodchip-manure bedding is re-used over a number of years, incrementally enriching the woodchip compost, before it is applied as a fertiliser. Finally, TerAvest et al. (2010) show that woodchip-derived compost suits wood growth when trialled over a suitable timeframe, in contrast to the rapid N uptake requirements of fast growing plants and grasses with lower lingo-cellulosic content.

Pill and Goldberger (2009) found that biosolid-woodchip co-compost limited growth of 'Beefsteak' tomato plants (*Lycopersicon esculentum*) during the first 6 weeks, in conditions where concentrations of co-compost exceeded 33.3 %; the remaining treatment media were made up of equal volumetric percentages of perlite and sphagnum peat moss, straight perlite, or straight peat moss. Furthermore, growth was reduced by excessive porosity and low water retention in treatments containing mostly perlite with < 33.3 % co-compost, but growth increased with higher concentrations of co-compost, due to the beneficial physical and nutritional characteristics of woodchip and biosolids, respectively. Similarly, Bugbee (2002) reported on a wide range of ornamental plants grown in 0, 25, 50, and 100 % woodchip–biosolid (3:1) compost, supplemented with a mixture of bark, peat and sand. Plants grown in the 50 and 100 % co-compost treatments were stunted and chlorotic for several weeks after planting, due to high salinity and ammonium levels, but recovered by mid-season and were among the fittest at the end of the growing season.

Soumare et al. (2002) trialled the same species of tomato plant (*Lycopersicon esculentum*) in Senegal, amended with ramial chipped wood (RCW) or litter compost. RCW consists of young growth, forest residues, and so would normally be expected to have a higher nutrient content than chips from older roundwood. Nevertheless, the study found RCW depressed tomato growth and yield, which it attributed to the woodchips inducing intense N immobilization in the soil due its high C:N ratio. The constituents of RCW are similar to 'yard trimmings' in the US, which Sullivan et al. (1998), found to have more than twice the slow-release N value of woodchip-sawdust media, under tall fescue (*Festuca arundinacea*).

In conclusion, woodchips used as weed suppressant surface mulch should be applied mid-season, or N enriched and incorporated if used as a soil amendment. Woodchip should not be applied to pre-emergent, or very young, vegetation unless fully mature.

4.5 Conclusions

The grassland trial was inconclusive, but indicated that woodchip-manure compost will be a suitable and valuable organic fertiliser once it has fully matured. Further, there is little agronomic benefit in annually sieving the woodchip-manure compost to extract the fine nutrient-rich fraction for fertiliser. This, however, is less significant than the economic benefit gained by separating the woodchip from the manure (after thermal kill compost temperatures have been achieved) to stop unwanted decomposition of the woodchips, in circumstances where the material is to be recycled as bedding the following winter. In addition, it is postulated that removing the manure fraction from the bedding-compost before storing the woodchips undercover will facilitate greater airflow throughout the pile during the summer, and result in bedding with lower moisture content for re-use the following winter. This is of critical importance, as the previous chapter showed, woodchips with low moisture content (< 35 %) have increased capacity to absorb excretal liquids during housing, which facilitated greater microbial activity and, thus, generated thermal kill compost temperatures during the early stages of composting. This is a regulatory, waste management requirement for the bedding to be safely recycled on an annual basis. In addition, findings from the B10 trial showed the ADAS C34 derivatives, with lower initial moisture content, yielded greater ($p > 0.05$) biomass than the ADAS C55, which had a higher initial moisture content. This indicates that the greater absorbency capacity of dryer woodchips not only improves the material's bedding and composting performance, but also that the benefits are transferred to crops via the sequestration and retention of available nutrients.

The number of years (lifespan) the woodchips would remain intact, and thus a viable bedding material, was not determined in the present study. Initial estimates of three years were based on a visual assessment of the 'well managed' Pontbren 3 year compost. However, it is understood this material was used as bedding for 1 winter season and then composted for 3 years. If the present project's woodchip management recommendations are deployed – composting the soiled bedding long enough to achieve thermal kill temperatures (65° C for at least 7 days), before stopping decomposition by separating the manure and woodchip fractions and storing the woodchips undercover to dry out until the following winter's housing period – it is feasible the bedding-compost may last for 5 years (or more), before the majority of chips are degraded. However caution should be taken, as this proposed estimate is purely for the purposes of extrapolating an economic lifespan of the woodchip material.

It is recommended that compost maturity be determined by analysis of C:N ratio and TN and DIN content, because a visual assessment may not be reliable. However, the B100 trial results showed that even with a weight-based nutritional disadvantage the 3 year old Pontbren woodchip compost had agronomic value in comparison with the conventional straw composts. It is suggested that microbial decomposition in the Pontbren compost had slowed to a very low rate, despite having a C:N ratio of 10:1, owing to critically low levels of available N, but the process was reinvigorated when the compost was mixed with topsoil at the start of the trial, making significant levels of N available to the barley. This is in agreement with the findings of Hadas and Portnoy (1994).

Comparison of the initial nutrient content in each treatment at the start of composting versus biomass yield at the end is not a simple one, due to unplanned complexities from having unbalanced (weight-based) amendment volumes. The consequence of this was that amounts of available nutrients and the extent the different material's physical properties influenced the physico-chemical and bio-chemical dynamics in each treatment medium during the trial. Therefore these trials would have been improved by applying amendments by % N rather than by weight.

4.6 References

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5.1 Introduction

This chapter uses economic modelling to present a range of applied scenarios. Following examination of nutrient dynamics that occurred during the composting of woodchip-derived manure (WM) that had previously been used for animal bedding, this paper assesses the economic viability and subsequent agronomic benefit of WM compost in a range of agricultural contexts. Because of the diversity of individual farming practices throughout Wales (e.g. farm size, livestock type, geographical location, infrastructure, proximity to suppliers etc.) this analysis was approached from a broad perspective, using applied case study examples to demonstrate a variety of potential scenarios involving the use of woodchip on farms. The aim was to provide the greatest number of farmers with an accurate and realistic assessment of using woodchip bedding under current market conditions. Where possible, costings are industry quotes, accurate at the time of writing. All costings should thus now be viewed as guides, although current prices can be inputted if desired.

5.2 Scenarios

Scenarios are based on two fundamental facts: 80 % of Welsh agricultural land is categorised as Less Favoured Area (LFA) and the national average holding size is 40 ha (see Table 5.3). Under Tir Gofal, a maximum of 72 Dairy, Suckler or Beef cattle younger than 24 months, or 480 breeding ewes (with or without lambs) are permitted on a 40 ha holding within a Disadvantaged Area. Beef cattle younger than 24 months were not used in these scenarios. The permitted number of livestock increases proportionately to 360 mature cattle, or 2,400 breeding ewes, on 200 ha.

In order to standardise the scenarios, a hypothetical set of parameters were developed:

1. Cattle and sheep are both housed for 8 weeks.
2. Bedding application rates for sheep consist of an initial 10 cm base layer followed by a 5 cm top-up layer per week, giving a total bedding depth of 45 cm; bedding application rates for cattle consist of an initial 15 cm base layer followed by two 5 cm top-up layers per week, giving a total bedding depth of 85 cm.
3. If woodchip is bought by weight, then moisture loss must be accounted for in the weight purchased. For example, 94.91 t of woodchip with 50 % moisture content (MC) fills the same volume (306 m^3) as 86.68 t at 30 % MC. ‘Green’ or ‘recently felled’ wood contains 45–60 % moisture, depending on the tree species and season.

4. All purchased woodchip, waste wood or round timber is assumed to have a 50 % MC, so must be stored either chipped or unchipped, until the woodchip is < 30 % MC, as recommended in Chapter 3.
5. The chipper model used in all the scenarios is a 6-year-old, ex-trade, Laimet HP 25. To hire a similar model costs approximately £100 for 1 day and £50 /day thereafter, 5 days hire is discounted to £50 /day.

This paper also assumes the (> 30 % MC) bulk density of G30 woodchip (chip sizes 1-3 cm) to be 3.224 m^3 t^{-1} (based on Simpson and TenWolde (1999) and Wood Fuels Handbook (Antonini and Bergomi, 2008)) and its cost to be £60 t^{-1} (English Wood Fuels, 2012), although prices vary considerably depending on location, season, wood type, moisture content and diesel prices at the time of purchase. The current market price of 'short round wood' suitable for chipping is £15 t^{-1}. Waste wood currently costs between £5 t^{-1} in Scotland and £55 t^{-1} in south-east England (Materials Recycling World, 2012). In these scenarios waste wood in Wales is estimated to cost between £5 and £15 t^{-1}, but prices may be surcharged if screening for metal fragments is needed before delivery (if, for example, the wood comes from broken pallets). Treated waste wood products are not suitable for woodchip bedding, as they may contain levels of copper, chromium and arsenic (CCA), creosote, light organic solvent preservatives (LOSP), micro emulsions, paints and varnishes. Farmers should ensure that any waste wood deliveries contain no treated materials before arrival.

Costs associated with giving production land over to grow wood for bedding are not included, as this is not considered an agronomic option for the majority of farmers in Wales, where the average holding is < 40 ha. Instead, it is assumed that farmers will use existing stands and then buy waste or recycled wood to supplement wood volumes if needed. Hedge cutting and woodland management are pre-existing annual costs, supported by the SFP scheme /Tir Gofal schemes, and farmers are encouraged, but not required under GAEC 15 to leave trimmings in situ to decompose. If farmers choose to buy a Laimet chipper, it is recommended that timber and waste wood is chipped green, because dry wood (particularly spruce) will quickly blunt the blade and dramatically increase the chipper's maintenance costs. Another word of caution is that farmers must not underestimate the area required to store the woodchip during the summer, although this can be achieved outside using a cover that will shed a large proportion of rainfall, while still allowing plenty of air movement (DTI, 2002).

The aim of storing the woodchips is to maximise moisture loss while minimising material decomposition. Temperatures within the pile should increase rapidly during the first month before stabilising, depending on the height of the pile, compaction and age of the material. The DTI

(2002) reports that, in loosely stacked 5 m high piles, temperatures stabilise at approximately 50° C, but that larger, compacted piles can reach > 80° C, increasing the risk of combustion. However, dangerously high temperatures are unlikely with the volumes of woodchip piles discussed in this paper. Therefore, active aeration using a lattice of piping (Rynk, 1992) or turning the woodchip piles during the summer, will reduce the woodchip's initial MC from > 50 % in recycled cattle bedding and from > 40 % in recycled sheep bedding (see Chapter 3, Figures 3.7 - 3.12), after the soiled bedding materials - woodchip and manure fractions – have been composted (ca. 6 weeks) to achieve PAS100 sanitization requirements. As discussed, woodchip piles should not be > 5 m high until the material is ≤ 30 % MC (DTI, 2002), after which the loosely stacked piles can be increased to 10 m high. A simple method can be used to calculate the space required for storing woodchips: taking the scenario above, where a farmer has 480 ewes housed for 8 weeks at a density of 1.33 m^2 $head^{-1}$, (480 × 1.33) is multiplied by the total depth (m) of woodchip that will be applied over the 8 weeks, (480 × 1.33) × 0.45 = 287 m^3. The area (m^2) required to store 287 m^3 of woodchip with > 30 % MC in 5 m high piles is √ (287 / 5) = 7.6 × 7.6 m, and the area (m^2) required to store woodchip < 30 % MC in 10 m heaps is, √ (287 / 10) = 5.4 × 5.4 m.

Notional cost of storage and handling

Hamelinck (2005) considers that commercial woodchip biomass stored in the open costs €1.1 m^{-3} yr^{-1}, which at current exchange rates (£0.8086 / €1) assigns a storage cost to 287 m^3 of £255.28 yr^{-1} or £0.89 m^{-3} yr^{-1}. This cost is discounted, however, against the cost of storing the equivalent volume of straw bedding (37.7 m^3 needed to house the same number of livestock). Although this is a smaller volume, straw stored in barns carries a higher opportunity cost than woodchip stored outside.

Likewise, mechanisms of dispersing each bedding type in the pens during winter housing depend on housing area and barn height. Straw is either broken up and strewn around the pens by hand or mechanically using a chopper to break-up and blow the straw into the bedding area. However, the chopped straw generates the ideal habit for mange mites, *Sarcoptes scabiei* var. *bovis*, which can leaded to intense irritation and less time spent lying down cudding, thus lower live-weight gains, or even weight loss (personal communications, N. Lowe, Wynnstay Feeds, 2012). Conversely, there are no reported cases of woodchip bedding supporting *Sarcoptes scabiei* var. *bovis* populations and the woodchip can be carried in a front-loader, tipped and then spread out, using the bucket to drag the chips around the pen. Labour and fuel costs involved in these different handling methods are considered to be comparatively balanced for smaller operations involving 72 cattle or 480 sheep, but increasingly disproportionate (woodchip bedding costs >

straw) at larger volumes, owing to the straw bedding's expansion factor In addition, the necessity of sieving the recycled woodchip bedding (estimated to be £3 /t, personal communications, K.A. Smith (ADAS)) and turning the woodchip piles (maximum 1 or 2 times) during the summer on a 40 ha holding, incurs fuel and labour costs. However, these costs are estimated to be similar to those incurred by the necessity to turn straw composts more frequently (6 to 8 times over the summer) - although, again, as the operating scale of a farm increases, so does the disparity in fuel and labour costs of storing and handling the different volumes of straw and woodchip.

The average bulk density of baled straw is 150 kg m^{-3} versus 40 kg m^{-3} loose (Kronbergs and Smits, 2008). Therefore straw has an expansion factor of 3.75. In addition, this figure can be used as a multiplier to calculate the volume of woodchip bedding required from a known volume of straw or vice versa. For example, 72 cattle require 306 m^3 of woodchip ((72 x 5 m^2) x 0.85 cm) = 306 m^3 or 81.6 m^3 of straw ((72 x 5) x 0.85) = 306 x 40 (kg m^{-3} loose straw) /150 (kg m^{-3} baled straw) = 81.6 m^3 or (306 m^3 woodchip /3.75 = 81.6 m^3 straw).

Because of the many differences in storage and handling requirements associated with each bedding type, a notional standard storage and handling cost of £1 t^{-1} yr^{-1} is applied to both woodchip and straw. This is a simplified cost structure, but it does have the benefit of accounting for the increasing differential in woodchip vs. straw bedding costs at larger stock volumes. The notional cost associated with housing 2400 cattle over 8 weeks on woodchip (£3,164) is £2,756 > straw (£408) whereas for 72 cattle the differential is £83 (£95 vs. £12).

Recycling a rolling stock

Compost volume (m^3) was not formally measured before and after the housing and composting periods. Instead it was visual estimated: except for moisture losses, there appeared to be little or no change in woodchip treatment volumes during the trial's composting period - and therefore, little or not change in the woodchip volumes available for the second winter's housing. Annual assessments of volumetric composting reduction between winter housing periods would be essential to inform farmers in advance, of the quantities of extra bedding needed to be chipped and dried ready for use. To compensate for this knowledge gap and ensure sufficient bedding over successive winters, an annual addition of 20 % of the initial volume of woodchip needed in year one has been accounted for, year on year. Chapter 3 showed the importance of the woodchip bedding's initial moisture content. If the woodchip moisture content is > 30 % at the start of housing, it is recommended that waste straw or extra manure is added to the soiled bedding after housing to ensure the compost briefly reaches thermal kill temperatures, before being sieved to stop further decomposition during storage over the summer.

5.2.1 Stocking densities (animals ha^{-1})

Under Tir Gofal, overall stocking rates should not exceed 2.4 livestock units (LSU) /ha where:

- 1 Dairy cow/Suckler cow = 1 LSU
- 1 Beef animal (> 24 months) = 1 LSU
- 1 Beef animal (< 24 months old) = 0.6 LSU
- 1 Breeding Ewe (with or without lambs) = 0.15 LSU.

On agriculturally improved grassland the rate is 2.4 LSU/ha; for other mandatory habitats, e.g. semi-improved grassland, stocking density should not exceed 1.0 LSU/ha overall. However, those rates can be modified on the basis that if the average rate is 1.0 LSU/ha for 12 months then it will be possible to graze 4.0 LSU/ha for 3 months (i.e., 4 times the average annual rate must not be exceeded), after which the area would then have to remain livestock-free for the remaining 9 months.

At present, 80 % of Welsh agricultural land is designated as a Less Favoured Area. In areas where this is the case, livestock producers are entitled to receive financial support under the Tir Mynydd scheme (WG, Tir Mynydd; 2007 – 2013) (the Welsh form of the Hill Livestock (Compensatory Allowances) scheme).

To qualify for the scheme, farmers have to have a maximum of 1.8 LSU/ha in Disadvantaged Areas and 1.2 LSU/ha in Severely Disadvantaged Areas. The scheme is due to end in 2013, as described under the Rural Development Plan (2010). For those farmers in receipt of Single Payment Scheme support payments, however, there are cross-compliance requirements (Statutory Management Requirements (SMRs) and Good Agricultural and Environmental Condition requirements (GAEC)). If breaches of these compliance requirements are found on inspection, then payments may be reduced, withdrawn or even recovered. GAEC9, which deals with avoidance of overgrazing and unsuitable supplementary feeding, does not specify a maximum grazing stocking density but requires that land and livestock be assessed on their condition. However, in recent years, bankruptcies and incentivized stock reductions have led to concerns of ecological succession from under-grazing in fragile upland and LFAs. So, for clarity, the following economic scenarios assume the use of Tir Mynydd maximum stocking densities in disadvantaged areas.

5.2.2 Housing densities (animals m^{-2})

5.2.2.1 Cattle

The WG Code of Practice for the Welfare of Livestock Cattle (2010) states that 'the space allowance should be worked out in terms of the whole environment; the age, sex, liveweight and behavioural needs of the stock; the size of the group and whether any of the animals have horns, and should be based on expert advice'. In line with these recommendations, the scenarios use the following space allowances $head^{-1}$ for cattle:

- Dairy, Suckler and Beef > 24 months - 5 m^2 $head^{-1}$
- Beef < 24 months - 3 m^2 $head^{-1}$.

5.2.2.2 Sheep

As this project focused on winter housing, space allowances for sheep were based on those deployed in the project's housing trials and the Welsh Government guidelines for pregnant lowland ewes:

- Pregnant Ewes - 1.33 m^2 $head^{-1}$.

The Welsh Government recommended space allowances are listed in Table 5.1 and can be found in the Code of Practice for the Welfare of Livestock: Sheep, March 2010.

Table 5.1: Welsh Government recommended space allowances for sheep

Lowland ewes (60 - 90 kg liveweight)	1.2 - 1.4 m^2 floor space / ewe during pregnancy.
Lowland ewes after lambing with lambs at foot up to 6 weeks of age	2.0 - 2.2 m^2 floor space / ewe and lambs.
Hill ewes (45 - 65 kg live weight)	1.0 - 1.2 m^2 floor space / ewe during pregnancy.
Hill ewes after lambing, with lambs at foot, up to 6 weeks of age	1.8 - 2.0 m^2 floor space / ewe and lambs.
Lambs up to 12 weeks old	0.5 - 0.6 m^2 floor space / lamb.
Lambs and sheep 12 weeks to 12 months old	0.75 - 0.9 m^2 floor space / lamb / sheep.
Rams	1.5 - 2.0 m^2.

Code of Practice for the Welfare of Livestock: Sheep March 2010

5.2.2.3 Organic livestock housing densities

Organic livestock space requirements shown in Table 5.2 are more generous than conventional densities, and the stock should ideally have access to outdoor areas as well:

Table 5.2: Minimum space requirements for organically farmed sheep and cattle in the UK

Stock	Weight	Soil Association indoor area requirement / head (m^2)	Minimum organic indoor area requirement / head (m^2)
Cattle	100 kg	2.6	1.5
Cattle	200 kg	4.4	2.5
Cattle	350 kg	7.0	4.0
Cattle	> 350 kg	8.7 with a minimum of 1.75 m^2 / 100 kg	5.0 with a minimum of 1 m^2 / 100 kg
Dairy cow		10.5	6
Bull		10 + 30 m^2 outdoor exercise area	10 + 30 m^2 outdoor exercise
Ewe		1.5	1.5
Ewe + lambs		2.0	2.0

Soil Association Organic Standards (2012) and Compendium of UK Organic Standards (2006)

5.2.3 Calculating the amount of bedding required

This is done by calculating the total depth of bedding (m) that will be applied over the entire housing period and multiplying it by the area (m^2) per animal. For instance, 72 dairy cattle that are housed at 5 m^2 for 8 weeks with an initial 15 cm layer and 10 cm top-up layers each week thereafter: 5 m^2 × 0.85 (depth, m) = 4.25 m^3 $head^{-1}$, multiplied by the total number of cattle being housed, 72 × 4.25 = 306 m^3. Principally, the calculation is the same for sheep, except the total depth of bedding will be less over 8 weeks (10 cm + (7 × 5 cm)) = 0.45 m^3.

To convert volume to tonnes, the value above is divided by the total volume by m^3 t^{-1}, depending on the woodchip's moisture content (see Table 5.7). For woodchip with 50 % MC; 306 (m^3) / 3.224 (m^3 t^{-1}) = 95 t. Organic dairy cattle housed at 6 m^2 $head^{-1}$; 6 × 0.85 = 5.1 m^3 $head^{-1}$ × 72 = 367.2 m^3 total volume of bedding, or 367.2 / 3.224 (50 % MC) = 114 t.

Straw bulk density and bedding volumes

Kronbergs and Smits (2008) report the average bulk densities of loose straw and baled straw are 40 kg m^{-3} and 150 kg m^{-3} respectively. Further, the mean weight of large Heston bales is 550 kg (500

– 600 kg) (Brears, 2012). This data is used to determine the following bedding volumes and costs of housing sheep at 1.33 m^2 $head^{-1}$ and cattle at 5 m^2 $head^{-1}$ over an 8 week period.

Sheep straw

480 sheep, housed for 8 weeks with an area allowance of 1.33 m^2 hd^{-1} require (1.33 × 0.45) × 480 = 287 m^3 of loose straw; 287 m^3 × 40 kg m^{-3} = 11.49 tonnes of straw, or 20.9 large Heston bales that take up a storage area of 76.6 m^3. The current cost of straw delivered to a farm in Wales is determined as £76 t^{-1}, by the overall mean of 2012 delivery quotes listed in Table 5.9. Therefore the straw bedding use over 8 weeks is 24 kg hd^{-1} costing a total of £873 or £1.82 hd^{-1}.

Cattle straw

As above, an initial 15 cm bedding layer covering 5 m^2 and weekly top-ups of 10 cm for 8 weeks, totalling 170 kg hd^{-1} or £12.92 hd^{-1} at £76 t^{-1}. The straw needed for bedding 72 cattle at 5 m^2 hd^{-1} for 8 weeks is 12.24 t (£930 at £76 t^{-1}), equivalent to 22 large Heston bales requiring a storage area of 81.6 m^3.

Table 5.3: Tir Gofal maximum number of livestock on 40 and 200 ha holdings and total weight of woodchip needed to house cattle and sheep over 8 weeks.

Land type, livestock category and equivalent LSU	Housing density m²	Maximum head on 40 ha	Total (t) woodchip bedding (50 % MC)	Maximum head on 200 ha	Total (t) woodchip bedding (50 % MC)
Agriculturally Improved Grassland					
Maximum of 2.4 LSU/ha					
Dairy or Suckler cow = 1 LSU/ha	5.00	96.0	127	480	633
Beef (> 24 months) = 1 LSU/ha	5.00	96.0	127	480	633
Beef (< 24 months) = 0.6 LSU/ha	3.00	160	127	800	633
Pregnant Ewes = 0.15 LSU/ha	1.33	640	119	3200	594
Semi-Improved Grassland					
Maximum of 1.0 LSU/ha					
Dairy or Suckler cow = 1 LSU/ha	5.00	40.0	52.7	200	264
Beef (> 24 months) = 1 LSU/ha	5.00	40.0	52.7	200	264
Beef (< 24 months) = 0.6 LSU/ha	3.00	66.7	52.7	333	264
Pregnant Ewes = 0.15 LSU/ha	1.33	267	49.5	1333	248
LFAs (cover 80 % of Wales)					
Disadvantaged Areas					
Maximum of 1.8 LSU/ha					
Dairy or Suckler cow = 1 LSU/ha	5.00	72.0	94.9	360	475
Beef (> 24 months) = 1 LSU/ha	5.00	72.0	94.9	360	475
Beef (< 24 months) = 0.6 LSU/ha	3.00	120	94.9	600	475
Pregnant Ewes = 0.15 LSU/ha	1.33	480	89.1	2400	446
Severely Disadvantaged Areas					
Maximum of 1.2 LSU/ha					
Dairy or Suckler cow = 1 LSU/ha	5.00	48.0	63.3	240	316
Beef (> 24 months) = 1 LSU/ha	5.00	48.0	63.3	240	316
Beef (< 24 months) = 0.6 LSU/ha	3.00	80.0	63.3	400	316
Pregnant Ewes = 0.15 LSU/ha	1.33	320	59.4	1600	297

Tables 5.4, 5.5 and 5.6 provide a range of costs head^{-1} for woodchip bedding, economic significance of moisture contents at different costs t^{-1}.

Table 5.4: Cost of woodchip £ head^{-1} of Dairy or Suckler or Beef cattle > 24 months, density of 5 m^{2} head^{-1} for 8 weeks with an initial 15 cm base layer and 7×10 cm top-up laye

Cost (£ /t)	20 % MC	30 % MC	40 % MC	50 % MC
£2 /t	2.32	2.41	2.52	2.64
£10 /t	11.62	12.03	12.58	13.18
£20 /t	23.23	24.07	25.16	26.36
£30 /t	34.85	36.10	37.74	39.55
£40 /t	46.47	48.13	50.33	52.73
£50 /t	58.08	60.16	62.91	65.91
£60 /t	69.70	72.20	75.49	79.09

Table 5.5: Cost of woodchip £ head^{-1} of Beef cattle < 24 months, when housed at a densit for 8 weeks with an initial 15 cm base layer and 7×10 cm top-up layers thereafter.

Cost (£ /t)	20 % MC	30 % MC	40 % MC	50 % MC
£2 /t	1.39	1.44	1.51	1.58
£10 /t	6.97	7.22	7.55	7.91
£20 /t	13.94	14.44	15.10	15.82
£30 /t	20.91	21.66	22.65	23.73
£40 /t	27.88	28.88	30.20	31.64
£50 /t	34.85	36.10	37.74	39.55
£60 /t	41.82	43.32	45.29	47.46

Table 5.6: Cost of woodchip £ head^{-1} of Pregnant Ewes, when housed at a density of 1.33 weeks with an initial 10 cm base layer and 7×5 cm top-up layers thereafter.

Cost (£ /t)	20 % MC	30 % MC	40 % MC	50 % MC
£2 /t	0.33	0.34	0.35	0.37
£10 /t	1.64	1.69	1.77	1.86
£20 /t	3.27	3.39	3.54	3.71
£30 /t	4.91	5.08	5.32	5.57
£40 /t	6.54	6.78	7.09	7.43
£50 /t	8.18	8.47	8.86	9.28
£60 /t	9.82	10.17	10.63	11.14

Table 5.7: Discrepancies in volume and weight between (softwood) woodchip moisture contents when buying by volume or weight

Woodchip % moisture	Volume (m^3 t^{-1})	Water cost when buying volume (£ t^{-1})	DW of Wood (t^{-1})	Water cost when buying weight (£ t^{-1})
0	3.69	0.00	10	0
10	3.67	0.03	9	6.00
20	3.66	0.11	8	12.00
30	3.53	0.77	7	18.00
40	3.38	2.03	6	24.00
50	3.22	3.79	5	30.00
60	3.13	5.46	4	36.00

Domestic fuels and livestock bedding require woodchips with less than 30 % MC. The woodchip supply chain in Wales is not currently geared to delivering calorific value, because of the time and space required to season the quantity of wood demanded. Hence, woodchip prices are variable and relatively high compared to straw. However, the Forestry Commission Wales (FCW) has agreed with the Centre for Alternative Technology (CAT) to store large quantities of felled wood on site in order to dry it out. The FCW has also agreed that once implemented, this measure will service the needs of both the domestic wood fuels and agricultural markets.

5.2.4 Straw

Table 5.8: Wholesale price t^{-1} of straw on 25th November 2012 by region across the UK mainland

	Pick-up baled barley straw (£ t^{-1})	Pick-up baled wheat straw (£ t^{-1})	Big sq. baled barley straw (£ t^{-1})	Big sq. baled wheat straw (£ t^{-1})
North East	70	-	58	42
East Yorks	-	-	55	45
N Midlands	68	-	55	40
E Midlands	-	-	55	39
C Midlands	70	50	50	38
E Counties	-	-	50	37
South-East	70	60	48	36
South	-	-	50	42
South-West	68	68	53	46
South Wales	70	55	58	48
SE Scotland	-	-	63	50

Prices supplied by the British Hay & Straw Merchants Association

Straw merchants use the prices in Table 5.8, supplied by the BHSMA and published in *Farmer's Weekly*, to determine where to buy the cheapest straw. Prices also differ between wheat and barley, as well as by bale size. Therefore, Wales' straw imports may come from anywhere in England - not just Shropshire or Norfolk - and a single delivery may consist of straw from a number of locations, depending on regional prices at different times. Quotes (£ /t) for deliveries to three locations in Wales (Bangor, Aberystwyth and Carmarthen, representing north, mid and south Wales) were obtained from three merchants in Shropshire: Church Stretton, Oswestry and Ludlow on 26th April 2008 and 25th November 2012. In 2008 the Ludlow and Oswestry merchants reported static prices since September 2007, whereas the Church Stretton merchant's prices had dropped £4 t^{-1}. By 2012, straw prices were reported as lower than 2011, but delivery charges continue to rise due to unprecedented diesel prices.

Table 5.9: Comparison of quotes (£ /t) given by three Shropshire straw merchants for Heston baled wheat straw on 26th April 2008 and 28th November 2012 delivered to three locations in Wales.

To	Bangor			Aberystwyth			Carmarthen		
From	**2008**	**2012**	Change	**2008**	**2012**	Change	**2008**	**2012**	Change
Church Stretton	£60	£75	+ £15	£60	£75	+ £15	£64	£75	+ £11
Oswestry	£65	£70	+£5	£70	£74	+ £4	£70	£79	+ £9
Ludlow	£65	£78	+ £13	£58	£78	+ £20	£70	£80	+ £10
Average	£63.33	£74.33	+ £11	£62.66	£75.66	+ £13	£68	£78	+ £10

In 2008, the wholesale price of straw, not the place of origin, determined the final price. The straw quoted by the Ludlow merchant (See Table 5.9) for delivery to Bangor in 2008 had been bought in Yorkshire (by road it is 280 miles from York to Bangor), whereas the Oswestry merchant had bought the straw delivered to Bangor from Cambridgeshire (it is 230 miles by road from Cambridge to Bangor), but at a slightly higher price - hence the deliveries arrived in Bangor at the same price. In November 2012, straw was still available in Shropshire, so distance to the destination determined delivery prices. Therefore, it is economic for farmers to use local merchants, unless they're going to purchase straw directly from the producer and collect it themselves.

5.2.5 Housing trials

Tables 5.10 and 5.11 contrast the bedding costs from the housing trials. Particular attention is drawn to the weight and cost of woodchip used head^{-1} in the two right hand columns.

Table 5.10: Total cost and cost animal^{-1} of woodchip used at IGER and ADAS

Livestock SITE	Chip used kg	Total cost £	Cost /t £ t^{-1}	Housing density m² head^{-1}	Weight of chip kg head^{-1}	Cost of chip £ head^{-1}
Sheep						
ADAS	13445	1035	76.99	0.95	149	11.50
IGER	3980	273	68.70	2.42	124	8.54
Cattle						
ADAS	15600	1212	77.70	5.64	650	50.51
IGER	14700	1032	70.19	6.45	1225	85.98

From Table 5.10 it can be calculated that the average cost of woodchip used under sheep (137 kg hd^{-1} at £72.85 t^{-1}) was £10.02 hd^{-1}. In contrast, the average cost of woodchip used under cattle (938 kg hd^{-1} at £73.95 t^{-1}) was £68.24 hd^{-1}.

Table 5.11: Total cost and cost animal^{-1} of straw used at IGER and ADAS

Site	Straw used kg	Total cost £	Cost /t £ t^{-1}	Housing density m² head^{-1}	Weight of straw kg head^{-1}	Cost of straw £ head^{-1}
Sheep						
ADAS	660	34.65	52.50	0.95	22.0	1.16
IGER	470	25.85	55.00	2.42	14.7	0.81
Cattle						
ADAS	1510	79.28	52.50	5.64	189	9.91
IGER	3555	195.53	55.00	6.45	296	16.29

Data in Table 5.11 show that the average cost of straw used under sheep (18.34 kg hd^{-1} at £53.75 t^{-1}) was £0.98 hd^{-1}. In the case of straw used under cattle (242.5 kg hd^{-1} at £53.75 t^{-1}) the cost was estimated to be £13.10 kg hd^{-1}. The different housing systems and area allowances deployed at each site and the variation in woodchip prices are reflected in the quantities of bedding used and the cost per animal. In both trials, straw was cheaper than woodchip.

5.2.6 Chippers

Laimet HP 25

New: £ 22,925 excl. VAT. £ 7,629 ex-trade 6 years old

The Laimet HP-25 chipper uses a conical screw blade, which also functions as a feed unit. There are five different chip sizes, ranging from 15–25 mm up to 60–100 mm, although it can produce chips up to 230 mm in diameter. The quoted output ranges from 40 to 120 $m^3\ hr^{-1}$ (12.5–37 $t\ hr^{-1}$), depending on the blade used as well as the size and type of wood. However, a Laimet HP-25 owner suggests that a maximum output of 12.5 $t\ hr^{-1}$ (depending on manpower) is a more realistic rate. This chipper is suitable for all types of clean wood: coniferous and deciduous, thinnings, tree tops, pruned and unpruned saplings, blocks, sawn surfaces and even frozen wood, but it should be noted that any timber or wood should be chipped green, because the Laimet's single blade will blunt quickly on dry wood, particularly spruce. The blade should be sharpened every full working day (8–10 hr). This can be done by the owner and takes approximately 20 minutes. Once the blade has worn down, it is more cost effective to have it re-tipped with hard welding than to buy a replacement - a new blade costs £4,805. The HP 25 design enables the owner to carry out maintenance themselves, so avoiding call-out costs.

Costs

Blade sharpening every 8–10 hrs	= £ n.a.
Blade re-tipping £1000 /600 hrs	= £ 1.66 /hr.
Anvil repair £100 /500 hrs	= £ 0.20 /hr.
Servicing £150 /250 hrs	= £ 0.60 /hr.
Output; 12.5 t /hr.	
Fuel Consumption; 2.5 ltrs /t	
Fuel Consumption; 31.25 ltrs /hr.	
Maintenance costs	**= £ 0.197 t^{-1}**

Data courtesy of Fuelwood Harvesting

Heizohack HM8-400

New: £ 25,695 excl. VAT.   £ 8,551 ex-trade 6 years old

The output of the Heizohack HM8-400 and the 8-400K (crane fed) are the same, as the infeed and drum size are identical on both machines. The factory output figure for this model is 40 m^3 hr^{-1}, (12.5 green t hr^{-1}) with conveniently stacked cord wood (1 cord = 128 ft^3 (4' × 4' × 8'), equivalent to 3.6 m^3, consisting of 66 % solid wood, 12 % air space and 22 % bark) or can be as much as 55 m^3 hr^{-1} when being loaded from a lorry or forwarder. The benefit of the hand-fed model over the crane-fed is apparent when feeding smaller diameter timber as the drum can be kept full.

The annual running costs for the chipper are obviously dependent on the type and volume of timber being chipped and any contaminants in the timber. The main wearing parts (as with any chipper) are the blades and the anvil. The design of the Heizohack blades are such that they allow 10 mm of sharpening; this equates to 5 sharpenings when cutting good clean timber with no contaminants. The HM8-400 blades need sharpening every 30–40 chipping hours (unless damaged by stones, nails etc.). For efficiency, three sets of blades are used in rotation: one in use, one spare set with the chipper, and one away being sharpened.

Costs

Set of eight blades (@ £10.00 each) = £240.00 excl. VAT

Average sharpening costs per set of blades = £24.00 excl. VAT

Rotating three sets of blades as above will give around 630 hours of chipping.

Anvil/shearbar = £230.00 excl. VAT

The anvil/shearbar is four-sided and in normal use will last approx 400 hours per side.

Blade costs = £240
Sharpening = £360 } = £600 /630 hours = £0.95 /hr.

Anvil costs = £230 divided by 1600 hours = £0.14 /hr.

Total blade and anvil costs = £1.09 /hr.

500 hr service costs (approximate) = £165 excl. labour & VAT.

Running costs (not incl. diesel or labour) = £1.42 /hr excl. VAT.

Data courtesy of A C Price

Greenmech CM 220 MT 55

New: £ 18,950 excl. VAT. £ 6,306 ex-trade 6 years old

The Greenmech 220 uses six disc blades mounted on a flywheel that have a fully sharpened circumference, so only a third of the cutting edge on each disc is in use at any one time - the rest of the cutting circumference is kept in reserve. The blades can be rotated to the next sharp section when performance is lost, giving less down time and a longer period between sharpenings than conventional flat blades or flail systems. The Greenmech 220 MT 55 is produced as both a PTO and a standalone unit with an output of 7 t hr^{-1}.

The blades need rotating every 50 chipping hours (unless damaged by stones, nails etc.), and then removing and sharpening every 150 hrs. Blades can be sharpened 6–10 times (1050–1650 hrs) before they need to be replaced. Replacement sets cost £177, or £29.50 /blade.

The Greenmech 220 has two anvils, which have a 4 – 5 yr. life-span (2000–4000 hrs under trade-use conditions). Each anvil costs £120 to replace or £240 for both. This should be taken into consideration if farmers are buying a second hand ex-trade chipper.

Costs

Sharpening set of six blades @ £50 /150 hrs	= £0.33 /hr
Blade replacement @ £177 set of 6 /1000 hrs	= £0.18 /hr
Anvil replacement @ £240 set of 2 /3000 hrs	= £0.08 /hr
Servicing @ approx £165 excl. labour & VAT	= £0.33 /hr
Running costs (not incl. diesel or labour)	**= £0.92 /hr excl. VAT.**

Data courtesy of Green mech Ltd

Jenson A328

New: £ 16,500 excl. VAT. £ 5,491 ex-trade 6 years old

The Jenson A328 model has been discontinued and replaced by the A340. It has two disc blades similar to the Greenmech 220. The anvil needs turning every 40 hrs and daily maintenance consists of torquing the blade bolts, greasing the feed roller shafts and checking the belt tension. Output is 5 t hr^{-1}.

Costs

Blade sharpening @ £50 /40 hrs	= £1.25 /hr
Blade replacement @ £300 /280 hrs	= £1.07 /hr
Anvil repair @ £25 /80 hrs	= £0.31 /hr
Anvil replacement @ £300 /280 hrs	= £1.07 /hr
Servicing @ £100 /500 hrs	= £0.20 /hr
Running costs (not incl. servicing, diesel or labour)	**= £3.70 /hr excl. VAT.**

Data courtesy of Elite Plant Hire and Arborcut

5.2.7 Depreciation costs

Depreciation is calculated using the reducing balance method. Buying an ex-trade chipper costs less initially, but may incur higher maintenance costs than a new chipper (Table 5.12). An ex-privately owned chipper is initially more expensive, so depreciation is higher with no guarantee of lower maintenance costs.

Table 5.12: Depreciation rates for new chippers and 'trade' chippers based on 500 – 800 working hours /yr, (private use is < 500 hours /yr).

Chipper model	New £	Trade: Year 1 25 % (£)	Trade: Year 2 15 % (£)	Private: Year 1 12.5 % (£)
Laimet HP 25	22,925	5,731	2,579	2,866
Heizohack HM8-400	25,695	6,424	2,891	3,212
Green mech 220 MT 55	18,950	4,738	2,132	2,369
Jenson A328	16,500	4,125	1,856	2,063

The scenarios in this report are based on a 6 year old ex-trade Laimet HP 25 which depreciates at 12.5 % pa. for < 500 operating hours /yr. Table 5.13 shows a selection of depreciation costs hd^{-1} of 480 and 2400 sheep (with an area of 1.33 m^2 hd^{-1}) and 72 and 360 cattle (with an area of 5 m^2 hd^{-1}). This simple method of dividing the annul depreciation cost by the number of livestock is justified because extra use of the chipper for reasons other than producing woodchip bedding cannot be anticipated, so the total depreciation is assigned hd^{-1} and not t^{-1}.

Table 5.13: Annual depreciation of four chipper models £ hd^{-1} under four different livestock regimes (480 and 2400 sheep and 72 and 360 cattle).

Ex-trade Model	6 yr. old ex-trade	Depreciation. 12.5 % (£)	Output $t\ hr^{-1}$	Annual Depreciation £ hd^{-1}			
				480 sheep	72 cattle	2400 sheep	360 cattle
Laimet HP 25	7,629	954	12.5	1.99	13.24	0.40	2.65
Heizohack	8,551	1,069	12.5	2.23	14.83	0.44	2.97
Green mech	6,306	788	7	1.64	10.93	0.33	2.19
Jenson	5,491	686	5	1.43	9.52	0.29	1.90

5.2.8 Chipper hire

The cost of hiring chippers in this capacity range is £100 for 1 day and £50 day^{-1} thereafter. 5 days hire is discounted to £50 day^{-1}.

The four livestock bedding volumes used in this report are detailed under 'Disadvantaged Areas' in Table 5.3: they are 480 sheep, 89 t; 72 cattle, 95 t; 2400 sheep, 446 t and 360 cattle, 475

t. The Laimet HP 25 has a output of 12.5 t hr^{-1}, so it is assumed that farmers with 480 sheep or 72 cattle on 40 ha holdings will only need to hire a chipper for one day, costing £100, and farmers or groups of farmers with 2400 sheep or 360 cattle will need to hire a chipper for 5 days, costing £250.

5.2.9 Running costs

Variable costs

Hydraulic oil cost:	£1.44 /ltr (Northern Wood Heat, 2012)
Motor oil cost:	£0.96 /ltr. (Northern Wood Heat, 2012)
Red Diesel Fuel:	72.55p /ltr. (Oct 2012) (DairyCo, 2012)

Hydraulic oil consumption:	£0.08 /hr. (Northern Wood Heat, 2012)
Motor oil consumption:	0.07p /hr. (Northern Wood Heat, 2012)
Fuel consumption (Laimet):	£22.67 /hr. (section 5.2.6)
Labour cost:	£14.50 /hr. (personal communication; Burton Nurseries 2012)

Total operating fuel and labour cost = £37.25 hr^{-1} or £2.98 t^{-1}

Maintenance costs

Table 5.14: Maintenance costs for different wood chippers (£ t^{-1}).

Maintenance	Action	**Laimet**	Heizohack	Green mech	Jenson
Blades	Sharpened	nil - DIY	0.05 t^{-1}	0.05 t^{-1}	£ 0.25 t^{-1}
	Re-tipped	£ 0.13 t^{-1} or	n/a	n/a	n/a
	Replaced	£ 1.66 t^{-1}	0.08 t^{-1}	0.03 t^{-1}	£ 0.21 t^{-1}
Anvil	Turn	n/a	Every 400 hrs. x4	n/a	Every 40 hrs.
	Repair	£ 0.02 t^{-1}	n/a	n/a	£ 0.05 t^{-1}
	Replace	n/a	0.01 t^{-1}	0.01 t^{-1}	£ 0.21 t^{-1}
	Service	£ 0.05 t^{-1}	0.03 t^{-1}	0.05 t^{-1}	0.04 t^{-1}
Fuel	ltrs t^{-1}	2.5	DNA	DNA	DNA
Output	t hr^{-1}	12.5	12.5	7	5
Running costs:	£ t^{-1}	**0.20**	0.17	0.14	0.76

DNA means data not available. n/a means not applicable

Total operating cost of a bought Laimet Chipper = £41.63 hr^{-1} or £3.33 t^{-1}

Total operating cost of a hired Laimet Chipper = £37.25 hr^{-1} or £2.98 t^{-1}

Additional costs

The haulage fuel costs of the different beddings are not determined, as they are accounted for in the delivery price.

5.3 Sensitivity analysis

This analysis estimates the cost of beddings (woodchip and straw) head^{-1} based on three forms of bedding material (wood, woodchip and straw) and two sets of livestock area allowances based on the WG Code of Practice for the Welfare of Livestock Cattle (2010) and housing densities used in the present study.

- 1 m^2, 1.33 m^2, 1.5 m^2, 2 m^2 and 2.5 m^2 hd^{-1} for flocks of 480 and 2400 sheep.
- 4 m^2, 4.5 m^2, 5 m^2, 5.5 m^2 and 6 m^2 hd^{-1} for herds of 72 and 360 cattle

Additional costs such as storage and handling and N loss (kg N) are determined for all bedding types. Further, chipping costs are determined for waste/recycled and/or home grown wood, based on whether a chipper is bought or hired.

In addition, the analysis extends over a 5 year time period, to show the average cost of each bedding type under each scenario (£ yr^{-1} over a 5 year period) and assumes that a farmer will produce the full volume of woodchip bedding needed for each herd / flock size in the first year, but in subsequent years will only need to produce 20 % of the initial bedding volume to replace any lost or degraded material, in order to maintain the same volume of bedding year on year. Hence, the project does not attempt to predict a definitive 'lifespan' for woodchip used as animal bedding but, rather, envisages a rolling stock of woodchip bedding that includes material of mixed age. Conversely, it is assumed the volume of straw bedding needed yr^{-1} remains the same.

The cost of raw materials is defined in three groups:

- Wood, (home grown and or waste/recycled) delivered with 50 % MC and then chipped, before being stored (priced at £5, £15 and £30 t^{-1}).
    - For home grown wood prices t^{-1} reflect different felling and collecting costs. Farmers with large, established stands are assumed to be able to fell and collect their wood at a lower price t^{-1} than a farmer with less trees or equipment.
    - The available price of waste/recycled wood will vary on a farm to farm basis around Wales, depending on location and personal contacts. South Wales has a large

furniture industry, and forestry is a major land-use throughout the country, so the average price t^{-1} is estimated at approx. £15 t^{-1} with a higher price of £30 t^{-1} to account for screening costs. For example, recycled pallet wood will need to be screened for metal, nails etc.

- Pre-chipped wood (woodchip), delivered with 50 % MC with a conversion factor of 3.224 m^3 t^{-1}, priced at £60 and £80 t^{-1} reflect current wood fuel prices at 50 % MC.
- The range of straw prices used (£50, £60, £70 and £80 t^{-1}), broadly reflect the prices farmers in Wales have paid for straw to be delivered over the last 5 years. Higher prices of £90 or £100 t^{-1} were not included because the analysis shows

Finally, the analysis also includes comparison of costs over time for buying *versus* hiring a chipper.

5.3.1 Determination of costs

Storage and handling

The notional storage and handling cost of £1 t^{-1} applied to both woodchip and straw beddings (see section 5.2), advantageously biases baled straw storage, which has a conversion factor of 6.66 m^3 t^{-1} compared to woodchip at 50 % MC 3.224 m^3 t^{-1} or 3.53 m^3 t^{-1} at 30 % MC, but this is ameliorated by the increased handling costs associated with larger volumes of woodchip bedding, such as sieving. Therefore, in the absence of any empirical data, this notional cost is considered satisfactory.

N loss

Differences in N loss between the project's two sheep trials suggest the high stocking density / low area allowance hd^{-1} at ADAS had a greater effect on N losses than the greater bedding volume hd^{-1} at IGER (see Table 5.15). However, there is a matrix of interacting factors influencing N losses during housing and composting, some of which have already been discussed in previous chapters. They include: livestock species and area allowance; bedding volume and frequency of top-ups (whether top-ups are targeted or broadcast); physical properties of the bedding material (absorbency of liquids and integration of solids); housing system (manure scrapped from the feeding area). Aside from those factors, N losses are particularly influenced by the types and quantities of feed offered hd^{-1} and by housing ventilation (rapid airflow across the bedding surface increases NH_3 loss).

Table 5.15: Bedding volumes (m^2 hd^{-1}) and N losses (kg hd^{-1}) from the sheep and cattle trials.

Trial	Sheep			Cattle		
Bedding	Area m^2 hd^{-1}	Straw kg hd^{-1}	Woodchip kg hd^{-1}	Area m^2 hd^{-1}	Straw kg hd^{-1}	Woodchip kg hd^{-1}
IGER	2.42	14.7	124	6.45	296	1218
ADAS	1.03	22.0	149	5.70	189	652
N loss	Area m^2 hd^{-1}	Straw g hd^{-1}	Woodchip g hd^{-1}	Area m^2 hd^{-1}	Straw g hd^{-1}	Woodchip g hd^{-1}
IGER	2.42	426	588	6.45	303	3362
ADAS	1.03	1159	1179	5.70	4970	6826

N loss from ADAS cattle is exaggerated by the removal of slurry during the trial, but no slurry was removed from the sheep pens. The ADAS sheep on straw (n=30) had an area allowance of 1.03 m^2 hd^{-1}, but received 22 kg of bedding hd^{-1} and lost 1159 g N hd^{-1}, compared to 2.42 m^2 hd^{-1} and 14.7 kg of bedding hd^{-1} which lost 426 g N hd^{-1}, at IGER. However, ADAS pregnant ewes (fed silage and concentrates) were not weighed after housing, so some of these recorded losses may be accounted for as live-weight gain. Therefore it is, unfortunately, not feasible to include incremental costs for N loss, based solely on different area allowances presented in this analysis. Instead a flat rate cost hd^{-1} has been applied, determined by the mean weight of N lost from ADAS and IGER's livestock/bedding combinations. The current cost of N is determined as £0.80 - 0.85 kg^{-1} (personal communications, Dr. K.A. Smith).

5.3.1.1 Costs specific to home-grown and waste/recycled wood

Fuel and Labour costs

The fuel and labour cost t^{-1} for using a Laimet HP 25 are defined under 'Variable costs' in section 5.2.9, determined as £2.98 t^{-1}

Annual depreciation cost

Annual depreciation of a 6 year old ex-trade Laimet HP 25 is defined in section 5.2.7; e.g.

£954 / 480 (sheep) = £1.99 hd^{-1}

£954 / 72 (Cattle) = £13.24 hd^{-1}

£954 / 2400 (sheep) = £0.40 hd^{-1}

£954 / 360 (Cattle) = £2.65 hd^{-1}

As depreciation costs are static for each livestock type/group size, they are presented in combination with maintenance costs as a summary of costs associated with buying a chipper.

Maintenance costs

The maintenance costs t^{-1} for using a Laimet HP 25 are defined in section 5.2.9, determined as £0.197 t^{-1}.

Tables 5.16 to 5.23 are summaries for sheep bedding only, showing cost $head^{-1}$ yr^{-1} in the first two years and the average cost yr^{-1} over a 5 year period, depending on the cost t^{-1} of parent materials and livestock area allowances (shown in the two left-hand columns). This selection of summary tables is presented to best illustrate the price sensitivities between straw and wood beddings. For example, cost variations between cattle beddings follow a very similar pattern to sheep, and straw bedding and pre-chipped wood costs are the same $head^{-1}$ for 480 sheep as for 2400, because the cost of N loss, storage and handling are proportionate. A full set of data tables displaying all associated costs described above are shown in Appendix VI. To reiterate, after the first year, an estimated 20 % of the initial bedding volume is needed to top-up the recycled bedding stock, hence lower woodchip bedding costs in year 2 and declining average annual costs over 5 years.

Table 5.16: Summary of bedding cost at different area allowances hd^{-1} in years 1 and 2 and the average cost hd^{-1} yr^{-1} over a total of 5 years for a farmer with 480 sheep to buy wood at £5, £15 or £30 t^{-1} and buy a chipper to produce woodchip on-farm.

Price of Wood £ t^{-1}	Sheep area m^2 hd^{-1}	Cost hd^{-1} in Year 1	Cost hd^{-1} in Year 2	Cost hd^{-1} yr^{-1} over 2 yrs.	Cost hd^{-1} yr^{-1} over 3 yrs.	Cost hd^{-1} yr^{-1} over 4 yrs.	Cost hd^{-1} yr^{-1} over 5 yrs.
5	1.0	3.80	2.89	3.34	3.19	3.12	3.07
5	1.3	4.22	3.01	3.62	3.41	3.31	3.25
5	1.5	4.44	3.07	3.76	3.53	3.41	3.35
5	2.0	5.08	3.26	4.17	3.86	3.71	3.62
5	2.5	5.72	3.44	4.58	4.20	4.01	3.90
15	1.0	5.20	3.17	4.18	3.84	3.67	3.57
15	1.3	6.08	3.38	4.73	4.28	4.06	3.92
15	1.5	6.54	3.49	5.01	4.51	4.25	4.10
15	2.0	7.87	3.81	5.84	5.17	4.83	4.63
15	2.5	9.21	4.14	6.68	5.83	5.41	5.15
30	1.0	7.29	3.59	5.44	4.82	4.51	4.33
30	1.3	8.86	3.94	6.40	5.58	5.17	4.92
30	1.5	9.68	4.12	6.90	5.97	5.51	5.23
30	2.0	12.06	4.65	8.36	7.12	6.50	6.13
30	2.5	14.45	5.18	9.82	8.27	7.50	7.04

Table 5.17: Summary of bedding cost at different area allowances hd^{-1} in years 1 and 2 and the average cost hd^{-1} yr^{-1} over 5 years for a farmer with 480 sheep to buy wood at £5, £15 or £30 t^{-1} and hire a chipper for one day at £100 day^{-1} to produce woodchip on-farm.

Price of Wood £ t^{-1}	Sheep area m^2 hd^{-1}	Cost hd^{-1} in Year 1	Cost hd^{-1} in Year 2	Cost hd^{-1} yr^{-1} over 2 yrs.	Cost hd^{-1} yr^{-1} over 3 yrs.	Cost hd^{-1} yr^{-1} over 4 yrs.	Cost hd^{-1} yr^{-1} over 5 yrs.
5	1.0	1.99	1.10	1.55	1.40	1.33	1.28
5	1.3	2.41	1.22	1.82	1.62	1.52	1.46
5	1.5	2.62	1.28	1.95	1.73	1.62	1.55
5	2.0	3.25	1.47	2.36	2.06	1.91	1.82
5	2.5	3.87	1.65	2.76	2.39	2.20	2.09
15	1.0	3.39	1.38	2.39	2.05	1.88	1.78
15	1.3	4.26	1.59	2.93	2.48	2.26	2.13
15	1.5	4.72	1.70	3.21	2.71	2.46	2.31
15	2.0	6.04	2.02	4.03	3.36	3.03	2.83
15	2.5	7.36	2.35	4.85	4.02	3.60	3.35
30	1.0	5.48	1.80	3.64	3.03	2.72	2.54
30	1.3	7.05	2.15	4.60	3.78	3.38	3.13
30	1.5	7.86	2.33	5.09	4.17	3.71	3.44
30	2.0	10.23	2.86	6.54	5.32	4.70	4.33
30	2.5	12.60	3.39	8.00	6.46	5.69	5.23

Table 5.18: Summary of bedding cost at different area allowances hd^{-1} in years 1 and 2 and the average cost hd^{-1} yr^{-1} over 5 years for a group of 5 farmers with 480 sheep each, to buy wood at £5, £15 or £30 t^{-1} and share the costs of buying a chipper to produce woodchip on-farm.

Price of Wood £ t^{-1}	Sheep area m^2 hd^{-1}	Cost hd^{-1} in Year 1	Cost hd^{-1} in Year 2	Cost hd^{-1} yr^{-1} over 2 yrs.	Cost hd^{-1} yr^{-1} over 3 yrs.	Cost hd^{-1} yr^{-1} over 4 yrs.	Cost hd^{-1} yr^{-1} over 5 yrs.
5	1.0	2.19	1.29	1.74	1.59	1.52	1.47
5	1.3	2.60	1.41	2.01	1.81	1.71	1.65
5	1.5	2.82	1.48	2.15	1.92	1.81	1.74
5	2.0	3.45	1.66	2.55	2.25	2.11	2.02
5	2.5	4.08	1.84	2.96	2.59	2.40	2.29
15	1.0	3.59	1.57	2.58	2.24	2.08	1.98
15	1.3	4.46	1.79	3.12	2.68	2.45	2.32
15	1.5	4.91	1.89	3.40	2.90	2.65	2.50
15	2.0	6.24	2.22	4.23	3.56	3.22	3.02
15	2.5	7.57	2.54	5.05	4.21	3.79	3.54
30	1.0	5.68	1.99	3.84	3.22	2.91	2.73
30	1.3	7.25	2.34	4.79	3.98	3.57	3.32
30	1.5	8.05	2.52	5.29	4.37	3.91	3.63
30	2.0	10.43	3.05	6.74	5.51	4.90	4.53
30	2.5	12.80	3.58	8.19	6.66	5.89	5.43

Table 5.19: Summary of bedding cost at different area allowances hd^{-1} in years 1 and 2 and the average cost hd^{-1} yr^{-1} over 5 years for a group of 5 farmers with 480 sheep each, to buy wood at £5, £15 or £30 t^{-1} and share the cost of hiring a chipper for 5 days at £50 day^{-1} to produce woodchip.

Price of Wood £ t^{-1}	Sheep area m^2 hd^{-1}	Cost hd^{-1} in Year 1	Cost hd^{-1} in Year 2	Cost hd^{-1} yr^{-1} over 2 yrs.	Cost hd^{-1} yr^{-1} over 3 yrs.	Cost hd^{-1} yr^{-1} over 4 yrs.	Cost hd^{-1} yr^{-1} over 5 yrs.
5	1.0	1.89	1.00	1.44	1.30	1.22	1.18
5	1.3	2.30	1.12	1.71	1.51	1.42	1.36
5	1.5	2.52	1.18	1.85	1.63	1.51	1.45
5	2.0	3.14	1.36	2.25	1.96	1.81	1.72
5	2.5	3.77	1.54	2.66	2.29	2.10	1.99
15	1.0	3.29	1.28	2.28	1.95	1.78	1.68
15	1.3	4.16	1.49	2.83	2.38	2.16	2.02
15	1.5	4.61	1.60	3.11	2.60	2.35	2.20
15	2.0	5.94	1.92	3.93	3.26	2.92	2.72
15	2.5	7.26	2.24	4.75	3.91	3.50	3.24
30	1.0	5.38	1.70	3.54	2.92	2.62	2.43
30	1.3	6.95	2.05	4.50	3.68	3.27	3.03
30	1.5	7.75	2.23	4.99	4.07	3.61	3.33
30	2.0	10.12	2.76	6.44	5.21	4.60	4.23
30	2.5	12.49	3.29	7.89	6.36	5.59	5.13

Table 5.20: Summary of bedding cost at different area allowances hd^{-1} in years 1 and 2 and the average cost hd^{-1} yr^{-1} over a total of 5 years for a farmer with 2400 sheep to buy wood at £5, £15 or £30 t^{-1} and buy a chipper to produce woodchip on-farm.

Price of Wood £ t^{-1}	Sheep area m^2 hd^{-1}	Cost hd^{-1} in Year 1	Cost hd^{-1} in Year 2	Cost hd^{-1} yr^{-1} over 2 yrs.	Cost hd^{-1} yr^{-1} over 3 yrs.	Cost hd^{-1} yr^{-1} over 4 yrs.	Cost hd^{-1} yr^{-1} over 5 yrs.
5	1.0	2.21	1.30	1.75	1.60	1.53	1.48
5	1.3	2.63	1.42	2.03	1.82	1.72	1.66
5	1.5	2.85	1.48	2.17	1.94	1.82	1.76
5	2.0	3.49	1.67	2.58	2.27	2.12	2.03
5	2.5	4.13	1.85	2.99	2.61	2.42	2.31
15	1.0	3.61	1.58	2.59	2.25	2.08	1.98
15	1.3	4.49	1.79	3.14	2.69	2.47	2.33
15	1.5	4.95	1.90	3.42	2.92	2.66	2.51
15	2.0	6.28	2.22	4.25	3.58	3.24	3.04
15	2.5	7.62	2.55	5.09	4.24	3.82	3.56
30	1.0	5.70	2.00	3.85	3.23	2.92	2.74
30	1.3	7.27	2.35	4.81	3.99	3.58	3.33
30	1.5	8.09	2.53	5.31	4.38	3.92	3.64
30	2.0	10.47	3.06	6.77	5.53	4.91	4.54
30	2.5	12.86	3.59	8.23	6.68	5.91	5.45

Table 5.21: Summary of bedding cost at different area allowances hd^{-1} in years 1 and 2 and the average cost hd^{-1} yr^{-1} over 5 years for a farmer with 2400 sheep to buy wood at £5, £15 or £30 t^{-1} and hire a chipper for 5 days at £50 day^{-1} to produce woodchip on-farm.

Price of Wood £ t^{-1}	Sheep area m^2 hd^{-1}	Cost hd^{-1} in Year 1	Cost hd^{-1} in Year 2	Cost hd^{-1} yr^{-1} over 2 yrs.	Cost hd^{-1} yr^{-1} over 3 yrs.	Cost hd^{-1} yr^{-1} over 4 yrs.	Cost hd^{-1} yr^{-1} over 5 yrs.
5	1.0	1.89	1.00	1.44	1.30	1.22	1.18
5	1.3	2.30	1.12	1.71	1.51	1.42	1.36
5	1.5	2.52	1.18	1.85	1.63	1.51	1.45
5	2.0	3.14	1.36	2.25	1.96	1.81	1.72
5	2.5	3.77	1.54	2.66	2.29	2.10	1.99
15	1.0	3.29	1.28	2.28	1.95	1.78	1.68
15	1.3	4.16	1.49	2.83	2.38	2.16	2.02
15	1.5	4.61	1.60	3.11	2.60	2.35	2.20
15	2.0	5.94	1.92	3.93	3.26	2.92	2.72
15	2.5	7.26	2.24	4.75	3.91	3.50	3.24
30	1.0	5.38	1.70	3.54	2.92	2.62	2.43
30	1.3	6.95	2.05	4.50	3.68	3.27	3.03
30	1.5	7.75	2.23	4.99	4.07	3.61	3.33
30	2.0	10.12	2.76	6.44	5.21	4.60	4.23
30	2.5	12.49	3.29	7.89	6.36	5.59	5.13

Table 5.22: Summary of sheep bedding costs hd^{-1} in years 1 and 2 and average cost hd^{-1} yr^{-1} over 5 years when woodchip is bought at £60, £80 or £100 t^{-1}.

Price of Woodchip £ t^{-1}	Sheep area m^2 hd^{-1}	W.chip £ hd^{-1} in Year 1	W.chip £ hd^{-1} in Year 2	W.chip £ hd^{-1} yr^{-1} over 2 yrs.	W.chip £ hd^{-1} yr^{-1} over 3 yrs.	W.chip £ hd^{-1} yr^{-1} over 4 yrs.	W.chip £ hd^{-1} yr^{-1} over 5 yrs.
60	1.0	9.05	2.35	5.70	4.58	4.02	3.69
60	1.3	11.86	2.95	7.40	5.92	5.17	4.73
60	1.5	13.30	3.25	8.28	6.60	5.77	5.26
60	2.0	17.56	4.16	10.86	8.63	7.51	6.84
60	2.5	21.82	5.07	13.44	10.65	9.26	8.42
80	1.0	11.84	2.91	7.37	5.88	5.14	4.69
80	1.3	15.57	3.69	9.63	7.65	6.66	6.06
80	1.5	17.49	4.09	10.79	8.56	7.44	6.77
80	2.0	23.14	5.28	14.21	11.23	9.75	8.85
80	2.5	28.80	6.47	17.63	13.91	12.05	10.93
100	1.0	14.63	3.46	9.05	7.19	6.26	5.70
100	1.3	19.28	4.43	11.86	9.38	8.14	7.40
100	1.5	21.68	4.93	13.30	10.51	9.12	8.28
100	2.0	28.73	6.40	17.56	13.84	11.98	10.86
100	2.5	35.78	7.86	21.82	17.17	14.84	13.44

Table 5.23: Cost of straw bedding hd^{-1} yr^{-1} for sheep, dependant on price (£50 - £100 t^{-1}) and livestock area allowance (1, 1.33, 1.5, 2 and 2.5 m^2 hd^{-1}).

Price of Straw £ t^{-1}	Sheep area m^2 hd^{-1}	Straw bedding £ hd^{-1} yr^{-1}
50	1.0	3.85
50	1.3	4.99
50	1.5	5.57
50	2.0	7.29
50	2.5	9.01
60	1.0	4.53
60	1.3	5.88
60	1.5	6.58
60	2.0	8.64
60	2.5	10.70
70	1.0	5.20
70	1.3	6.78
70	1.5	7.60
70	2.0	9.99
70	2.5	12.39
80	1.0	5.88
80	1.3	7.68
80	1.5	8.61
80	2.0	11.34
80	2.5	14.08
100	1.0	7.23
100	1.3	9.48
100	1.5	10.63
100	2.0	14.04
100	2.5	17.45

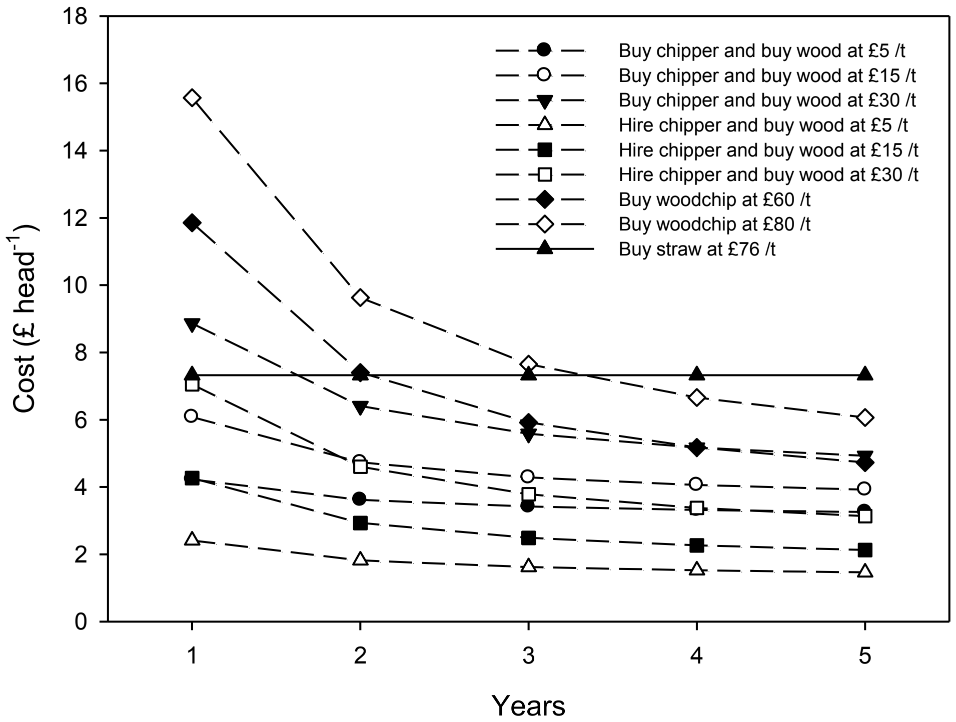

Figure 5.1 (above): *Comparison of bedding options and associated costs (£ hd^{-1} yr^{-1}) for sheep at 1.33 m^2 hd^{-1} over a 5 year period. Straw bedding costs are fixed at the current market price (76 t^{-1} yr^{-1}) and contrasted against a range of typical woodchip price options.*

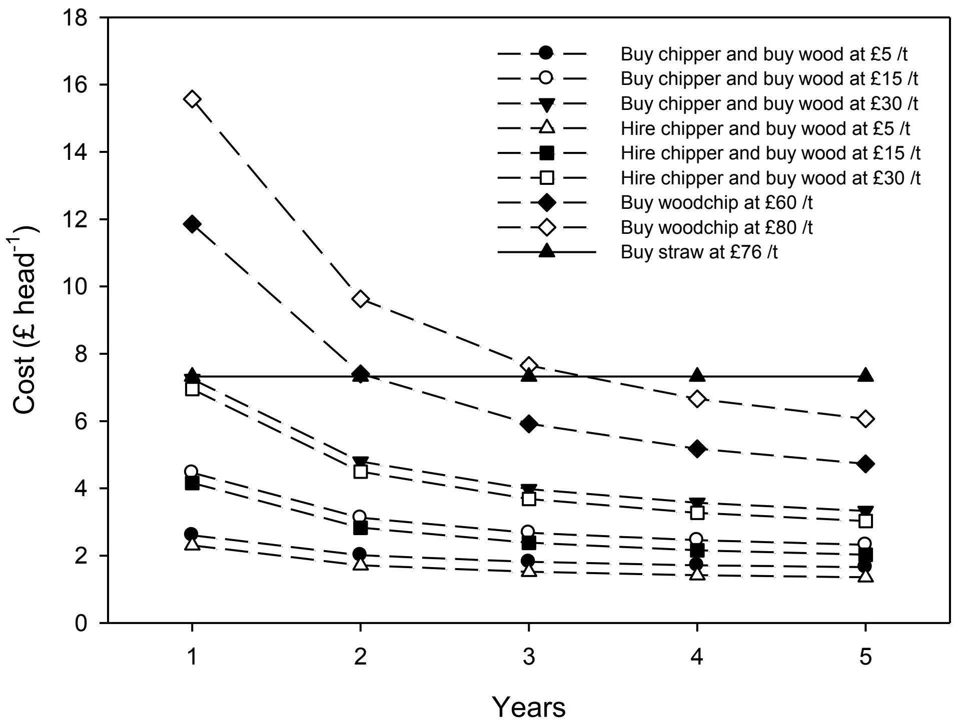

Figure 5.2 (above): *Comparison of bedding options and associated costs (£ hd^{-1} yr^{-1}) for sheep at 1.33 m^2 hd^{-1} over a 5 year period when a group of 5 farmers with 480 sheep or 72 cattle, buy or*

hire a chipper. Straw bedding costs are fixed at the current market price (76 t^{-1} yr^{-1}) and contrasted against a range of typical woodchip price options.

Sensitivity to changes in price of raw bedding materials

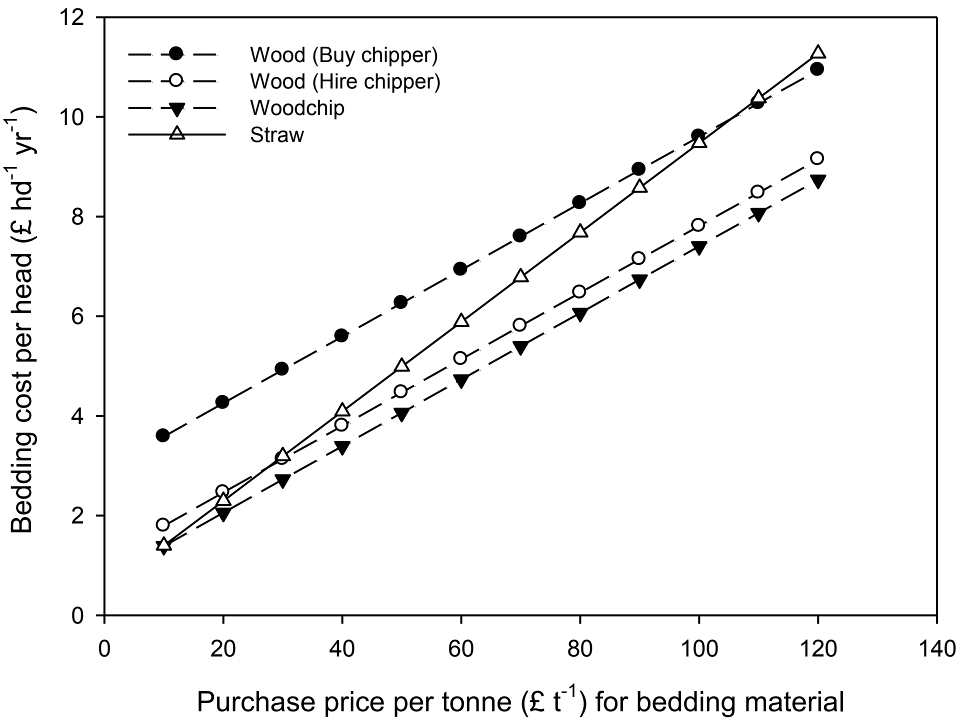

Figure 5.3: *Effect of purchase price of bedding material on the cost (£ hd^{-1} yr^{-1} over 5 yrs.) for sheep at 1.33 m^2 hd^{-1}*

Table 5.24 shows the incremental change in cost hd^{-1} (sheep, in Yr. 1 when 100 % bedding volume is required and Yr. 2 (onwards) when 20 % volume is required), and mean incremental change in cost hd^{-1} (sheep, over 5 yrs.), transferred by every £1 t^{-1} ± change in price of bedding material.

Sheep area m^2 hd^{-1}	Cost inc. hd^{-1} (£) for every £1 t^{-1} (±) of wood or chips in Yr. 1	Cost inc. hd^{-1} (£) for every £1 t^{-1} (±) of wood or chips in Yr. 2	Cost inc. hd^{-1} yr^{-1} (£) for every £1 t^{-1} (±) of wood or chips over 5 yrs.	Cost inc. hd^{-1} yr^{-1} (£) for every £1 t^{-1} (±) of straw over 5 yrs.
1.0	0.14	0.03	0.05	0.07
1.3	0.19	0.04	0.07	0.09
1.5	0.21	0.04	0.08	0.10
2.0	0.28	0.06	0.10	0.14
2.5	0.35	0.07	0.13	0.17

Table 5.25 shows the incremental change in cost hd^{-1} (cattle, in years 1 and 2), and mean incremental change in cost hd^{-1} (cattle, over 5 years), transferred by every £1 t^{-1} ± change in price of bedding material.

Cattle area m^2 hd^{-1}	Cost inc. hd^{-1} (£) for every £1 t^{-1} (±) of wood or chips in Yr. 1	Cost inc. hd^{-1} (£) for every £1 t^{-1} (±) of wood or chips in Yr. 2	Cost inc. hd^{-1} yr^{-1} (£) for every £1 t^{-1} (±) of wood or chips over 5 yrs.	Cost inc. hd^{-1} yr^{-1} (£) for every £1 t^{-1} (±) of straw over 5 yrs.
4.0	1.05	0.21	0.38	0.51
4.5	1.19	0.24	0.43	0.57
5.0	1.32	0.26	0.47	0.64
5.5	1.45	0.29	0.52	0.70
6.0	1.58	0.32	0.57	0.77

In Tables 5.24 (sheep) and 5.25 (cattle), the incremental changes in cost hd^{-1} and average cost hd^{-1} are the same for buying all wood-based bedding; whether it be woodchip (chips) or wood (or whether the wood is bought and chipped by a group, or a single farmer, who buy or hire a chipper). Because the volume of bedding needed is dependent on each livestock area allowance and not the method of producing the bedding.

Both Tables 5.24 and 5.25 show that in year one (Yr.1), using straw bedding carries a lower incremental cost or saving per £1 t^{-1} change in price of raw bedding material than wood-based bedding. In year two (Yr.2) the pattern is reversed: wood-based bedding has a lower increment cost/saving than straw, owing to the provision that only 20 % of year one's bedding volume is required to top-up the recycled bedding stock. After 5 years the average incremental cost/saving hd^{-1} of sheep and or cattle is lower for wood-based bedding than straw.

5.4 Discussion

Figure 5.1 shows that in year 1, buying pre-chipped wood at £80 or £60 t^{-1} or buying a chipper and wood at £30 t^{-1} is more expensive hd^{-1} than buying straw bedding at the current market price of £76 t^{-1} including delivery. However by year 2, it is more cost effective to either own or hire a chipper and buy wood for < £30 t^{-1} than it is to buy straw; by year 3, the only option more expensive yr^{-1} than straw is buying pre-chipped wood at £80 t^{-1}. In year 4, use of straw bedding is the least economic option and the average yearly cost hd^{-1} for using woodchips continues to fall.

If a group of farmers, each with 480 sheep (or 72 cattle) shares the cost of buying or hiring a chipper, then the use of woodchip bedding becomes a more economic option than straw even more quickly. Figure 5.2 illustrates that without exception, a co-operative of farmers would benefit from sharing the costs of producing woodchip bedding on-farm if wood is bought for £30 t^{-1} or less, in contrast to using straw bedding at the current market price - even in year one when the full initial bedding volume must be produced. In addition, the average cost hd^{-1} yr^{-1} continues to fall and, by year 5, using woodchip bedding produced on-farm is twice as cost-efficient as buying straw.

Figure 5.3 illustrates at the prices t^{-1} at which straw bedding is a more or less economic option yr^{-1} over a 5 year period than woodchip bedding derived by different means. At £10 t^{-1} straw bedding is a more economic option than buying wood to produce woodchip bedding on-farm, and equal to the cost of buying woodchip. However, under current market conditions neither straw nor woodchip are likely to be available at less than £50 or even £60 t^{-1} and within that price range, woodchip delivered to the farm continues to be a more economic option than straw. At > £30 t^{-1}, straw use becomes less economic than buying wood and hiring a chipper, although £30 t^{-1} is considered a high price for waste/recycled or home grown wood, it is not for straw; as such, buying wood and hiring a chipper is more economic than using straw. The option of buying wood at < £30 t^{-1} and buying chipper results in lower average bedding costs $head^{-1}$ yr^{-1} than straw, when straw prices are > £50 t^{-1}.

In combination, Figures 5.1 to 5.3 and Tables 5.24 and 5.25 show that using wood-based bedding is cheaper than straw in the long term, and that wood is less sensitive to fluctuations in the purchase price t^{-1} than straw.

A simple but effective system, widely used in Scandinavian countries for drying large quantities of woodchip, is to lay a perforated pipe or lattice of pipes underneath the woodchips, attached to a compressor that blows air through the piles - similar to aerated static composting (Rynk, 1992). This not only reduces the length of time required to dry the woodchip, but also achieves lower moisture content than just leaving them to air-dry naturally. It has not been possible to find out the cost involved, but for large quantities of stored woodchip, it would certainly seem very beneficial.

Looking ahead, it is expected climate variability, in combination with shifting market demands, government policies and incentivised schemes, will continue to put pressure on straw production in the UK. A summary publication by the UK Government, (Met. Office, 2012) reports (with moderate - low confidence) that by 2100, temperatures in the south of the UK will increase by up to 3 °C and by up to 2.5 °C further north. In addition, rainfall levels are confidently predicted to increase in northern Europe (by up to 10 %) and decrease in southern Europe (by up to 5 %). However, the scientific community is less confident about the latitude of the transition zone, suggesting precipitation levels will generally increase in southern England, but some areas may decrease by up to 5 %. Consequently, the study is non-committal on crop yield projections, but suggests yields are likely to increase in N. Ireland and Scotland and decrease in the south. To counteract this climatic uncertainty, plant breeders will continue to develop broad spectrum varieties, such as types with greater rough resistance, capable of meeting and maintaining the UK's food security. Meanwhile, the biomass industry's demand for organic material will not relent in the short to medium term. Delivand et al. (2011) show large-scale rice-straw fuelled combustion projects in Thailand would remain viable if the selling price of electricity dropped by 16 % (based on \$0.0758 USD /kWh) and the biofuel price increased by 36 % (based on \$31.0 USD/t)) over a forecast 20 year lifespan. Clearly, if such an operating buffer capacity were to be realised in UK biofuel production facilities, organic material for agric-bedding use would quickly be priced out of the market.

In Croatia, wheat straw, corn stover and forest residues are currently considered the most financially viable cellulosic biofuels, with an average energy potential in wheat straw of 8.5 PJ; in corn stover, 7.2 PJ; and in forestry residues, 5.9 PJ (Cosic et al., 2010). In addition, Simon et al. (2010) evaluated the economic radius of using crop residues and dedicated energy crops to supply 200-million-litre biodiesel plants in France. Their results show cereal straw and corn stover biomass would be viable up to 58 km to 168 km from the plant, depending on the crop residue and its abundance. But the cost of supplying a plant with the energy crop miscanthus is much higher. Thus it can be concluded that crop residues offer a lower cost to the producers of biodiesel in the near term than a dedicated crop; therefore, in a country the size of the UK, with its distinct arable regions, it would take only a couple of strategically located large-scale biodiesel plants to consume the entire straw market. In combination, these two European studies suggest a continuing upward trend in straw demand, and thus price. While the biomass industry demand on the UK wood stock is mitigated by imports, pressure on UK straw availability cannot be mitigated in the same way;

even importing torrified straw would increase costs, thus reducing its competitiveness over domestic prices. However, if sufficient volumes of low cost straw could be imported, domestic straw prices would still be vulnerable to many of the pre-existing issues highlighted above.

If a situation is reached where costs for organic bedding become completely untenable, one possible solution would be the use of synthetic materials. Rubber matting is hygienic, re-usable and resilient. In addition, Norring et al. (2010) conducted a behavioural study of cattle housed on rubber matting, sand and concrete flooring, with small quantities of bedding. Although concrete and sand are not the most challenging comparisons, cattle did prefer the rubber matting. In contrast, however, Lindner and Hoy (1997) studied broiler hen ethology and hygiene on three bedding treatments: deep litter woodchip (with and without mixing) and straw. They concluded that hen behaviour and cleanliness indicated that unmixed deep litter woodchip beddings, topped-up every 5 days, was the preferred treatment – providing economic costs allowed.

Aleksandra et al. (2006) analysed the microbial dustiness of baled straw (conventional and organic) and of woodchips from piles that had been stored outdoors for up to 11 months, using total spore count, cultivation, and measuring of endotoxin and chemical markers of fungal biomass, lipopolysaccharide and peptidoglycan. Overall the study found dustiness was greater in the centre than on the surface, except for fungal and bacterial biomass in woodchips, and fungal biomass in organic straw. In addition, organic straw contained considerably less bacterial dust than conventional straw, but bacterial dustiness increased in both straw types due to summer storage, although less so in organic straw. Although this study describes standing biofuel stockpiles, the findings are directly applicable to organic livestock beddings considered in this project, and highlight the considerable human and animal health benefits of using and storing of woodchips compared to straw.

5.5 Economic conclusions

In combination, Figures 5.1 to 5.3 show that under typical livestock housing conditions (1.33 m^2 $sheep^{-1}$), buying wood and or woodchip as livestock bedding is a more economic option than straw, particularly if a group of farmers share the costs of buying a chipper, and more so if a group of farmers share the cost of chipper hire, based on the study's recommended criteria that the woodchip bedding is annually recycled, after BSI PAS100 thermal kill sanitization, then separated from the manure fraction before being stored and replenished with an estimated 20 % of the initial bedding mass. The analysis includes a range of purchase prices for wood, woodchip and straw as well as livestock area allowances, but other possible permutations of this economic model could be made. For example, a farmer may find that the recycled bedding stock required an annual addition of 15 % or 25 % woodchip, or that achieving 30 % moisture content in the recycled bedding stock, before the start of the following year's winter housing period, required more pro-active management approaches (such as those discussed in section 5.4), which would in turn increase the handling cost of woodchips, in relation to straw. Equally, the notional storage costs applied to one or both bedding materials may be inaccurate: e.g. A farmer may decide not to compost straw bedding after housing and apply it straight to the land instead, thereby eliminating the cost of compost management (albeit at the expense of potentially greater N loss and disease transfer). Measurements of N losses via different pathways (Moral et al., 2012), under a range of housing conditions would add depth and definition to this analysis by enabling an incremental cost of N loss kg^{-1} for different area allowances and elucidating whether an optimal area allowance for sheep and for cattle on each bedding type exists, or whether N losses differ due to the different interactions and integration of the manure and bedding fractions. The analysis may be enhanced further by scaling down the required bedding volumes at larger area allowances. Cattle bedding volumes and area allowances increased concurrently in the present study, but logic suggests the frequency of top-up applications required by livestock with greater area allowances would be less than under livestock in more densely stocked housing units; thus total bedding volumes would remain roughly the same. However, an adjustment to standardising bedding volumes across different area allowances would not alter the study's main finding, that woodchip is a more economic bedding material for Welsh farmers than straw when used long term and in accordance with the criteria set out in this report.

5.6 References

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6.1 Conclusions

The woodchips, with their low surface area and dense rigid shape, did not homogenise with the nutrient-rich manure inputs, resulting in: 1) more bedding being applied and thus a higher bedding-to-manure ratio, which resulted in high total C:N ratios in the compost after housing (this point will be discussed later); and 2) a large amount of manure being retained on the surface above the bedding, from which NH_3 was readily volatilized, following rapid ammonification during housing. Furthermore, it was observed that large, flat, splinter-shaped woodchips compacted more readily than small cubic woodchips, reducing woodchip-manure integration and, potentially, further increasing NH_3 emissions. In addition, but to a lesser extent, significant quantities of NH_4^+, K, Na, and Ca were lost in excretal liquids that passed freely through the bedding. However, woodchips with initially lower moisture contents had a greater capacity to absorb nutrient-rich excretal liquids, resulting in them having significantly higher nutrient contents after housing than woodchips with initially high moisture contents. However, the scale of this nutritional advantage was only relevant between woodchip beddings and not in comparison to straw bedding-composts, which proved far superior. The straw bedding lost a similar amount of N during housing, partly because the area allowances, pen sizes, dry matter intake and feed types offered to the livestock on the two bedding types within each of the four livestock trials (sheep and cattle at ADAS and IGER) were balanced. However, straw lost N for different reasons: the material has a larger surface area, lower lignin content and thus less structural rigidity. This allows the bedding and manure to mix more easily, and thus less bedding was required. However, the low biomass-to-manure ratio still meant manure inputs were exposed to surface losses of NH_3; although straw is more absorbent than woodchip by weight, less bedding volume still resulted in liquid nutrient loss in seepage. Fresh straw has a lower total C:N ratio than wood, combined with a lower biomass-to-manure ratio. This resulted in the straw bedding-compost having a significantly lower total C:N, and higher concentrations of labile C and N than woodchip.

Once composting began, the structural differences between wood and straw beddings resulted in them having different biomass-to-manure ratios and physico-chemical characteristics. Total C:N ratios in the woodchip composts were high, owing to both the quantity of wood present (biomass-to-manure ratio) and original total C:N ratio of wood, thus having a proportionately low manure content and low available C:N ratio. This was compounded by a wider deficiency in a range of soluble salts that were lost in seepage during the bedding phase, leaving insufficient quantities remaining in the compost for microbial growth and activity. This resulted in low compost temperatures and slow decomposition rates, except in the drier woodchips, which achieved thermophilic temperatures and BSI PAS100 sanitation required for recycling the bedding the following winter. With both available C and N at such low concentrations, N loss from the woodchip composts was negligible during composting phase, owing to microbial immobilization. Although, leaching is thought (data not recorded) to have continued throughout composting, evidenced by the reduction in cations K Na and Ca. Normally, cations are not easily leached, due to their electro-static attraction to negatively charged colloidal surfaces that are prevalent in soils, but not in wood. Decomposition of the woodchip composts was not only limited by deficiency of available nutrients, but also by the high percentage of complex lignin compounds in the wood. Decomposition of lignin's complex lattice structures is initiated by peroxidase enzymes produced by white rot fungi. Thus the bacterial community is entirely dependent on the establishment of these fungi before the nutrients bound up in the wood become available.

Consequently, the nutrient deficiencies in the woodchip composts were evident in the plant growth trials. The grass trial showed there was no significant difference in biomass yield, and thus agronomic value, in 1 year old woodchip amendments compared to the zero addition control. In addition, it was thought that the 3 year old woodchip composts were mature and, thus, would have significantly greater agronomic value than 1 year old woodchip composts. However, the results showed that both 1 and 3 year old woodchip composts had similarly low available N contents (ca. 0.31% of total N in both), and the trial was considered inconclusive.

The B10 and B100 barley trials set out to determine the agronomic value of sieving the woodchip bedding-composts to extract the fine (<8 mm) fraction, thought to be rich in nutrients, and subsequently applied at rates of 10 and 100 t ha^{-1} respectively. However, biomass yield from the fine fractions of 1 year old woodchip amendments (10 t ha^{-1}) was lower than from the coarse fraction and the results were inconclusive at 100 t ha^{-1}. The trial emphasized the low levels of available N loss during housing and subsequent immobilization during composting.

These conclusions may seem negative, by focusing on the woodchip bedding-compost's nutrient deficiencies. However, N losses could be mitigated during housing by removing or limiting N loss from the manure, by:

- Removing slurry from the feed area during housing, to reduce the volume of exposed manure and thus NH_3 loss and (in addition) reducing the volume of bedding needed and frequency of top-up applications (leading to material and labour cost savings).
- Equipping housing units with drainage capture system to prevent nutrient seepage, particularly under cattle with greater volumes of excretal liquids.
- Ensuring the woodchip moisture content is < 30% when it is applied as bedding, increasing the absorbency capacity of the bedding and facilitating sufficient

microbial activity to achieve the essential BSI PAS100 thermal kill composting temperatures.

- Targeting heavily soiled areas of the bedding layer when applying top-ups to reduce the amount of manure exposed to the air and lessen NH_3 volatilization, following the methods of Gilhespy et al. (2009) for limiting NH_3 emissions from straw bedding.
- Adding removed slurry to slurry pits/lagoons, with the aim of limiting further N losses.

These strategies may also be applied to straw bedding to limit N loss. However, because the production and haulage of wood within Wales is likely to require less diesel and fertilizer than conventionally grown, annual wheat or barley straw bales transported from Yorkshire, Shropshire or Norfolk, woodchip is considered a more environmentally sustainable bedding than straw. In addition, if this study's recommendations for using and recycling woodchip bedding are practicable, then woodchip is a more economic bedding option than straw after 1 to 4 years of re-use, and the transferred costs (hd^{-1} of livestock) are less sensitive to price fluctuations in the raw material.

This project recommends using 1 to 3 mm sized cubic woodchips with ca. 30% moisture content, in addition to removing manure from feed areas and using drainage capture during housing. Between housing periods, the soiled bedding must be actively composted for ca. 6 weeks to ensure the material is sanitized, before being sieved and stored in piles 5 m high to dry over the summer, which can be increased to 10 m, but only if the woodchip's moisture content is < 30%. An estimated provision of 20% (initial bedding volume) per year, should be produced and added to the sanitized bedding stock after it has been separated from the manure fraction, to compensate for volume losses during housing and sieving, as well as degradation of chips during storage. The growth trials conducted here indicated that mature woodchip-manure compost will be of agronomic value as an organic fertilizer. Alternatively, the spent woodchip could be added to a slurry lagoon, where it may reduce N losses before being decomposed.

In broad terms, this study adds to the existing scientific understanding of woodchip use within livestock agriculture, but this study is unique in specifically investigating the use of woodchip as a recyclable, indoor bedding commodity and identifying its conditions of use throughout the material's entire lifecycle. Consequently, the scope of this study has elucidated many areas where further research is needed (see section 6.2.2).

6.2 Recommendations and further research

6.2.1 Improvements to the present study

Replication and standardisation of experimental treatments are prerequisites of scientific investigation. The omission of these procedures from the trial protocols was no one institution's responsibility or oversight, but a collective decision based on funding and the essential requirements necessary to fulfil the Welsh Government's objectives. Nevertheless, this does not detract from the considerable value of the work untaken. Indeed, at the time this project was executed there were few, if any, studies that specifically examined the practical and economic suitability of woodchip as an indoor livestock bedding material. Therefore, while it should be understood that this is far from a definitive study, it is hoped that the work provides a useful platform from which future research will benefit.

Summary of essential and recommended improvements:

1. Standardization of housing protocols to allow direct comparison between treatments:
   - Scraped areas – either use them in all treatments or none.
   - Bedding quantities and housing densities (stocking densities). Protocols must include standardised space allowance /head and bedding depths depending on the duration of housing period.
   - Feed types and quantities (including supplements) should be identical in trials where feed is not a tested variable.
   - A metered and appropriate drinking water dispenser, so livestock can drink *ad lib* but quantities/head/day are recorded (this data would be interesting to compare with different feed types) and 'an appropriate dispenser' - i.e. not a bucket in the corner which can be kicked over. If the volume of seepage was collected from the stalls this would allow a water mass balance to be calculated.
   - The same flooring must be applied to all treatment pens. Preferably, this would allow collection of seepage to determine nutrient loss rates.
   - Determine the mass of composts, both intermittently during the active composting phase and at the end of composting period and during the maturation phase, if undergoing long-term storage. This will allow calculation of dry matter loss after accounting for moisture content.
   - Standardisation and regulation of moisture contents during composting.

- Standardised woodchips shapes, age and species of wood. Greater characterisation of the wood porosity and water holding capacities would also be beneficial.

2. Four or more replicate pens of each experimental treatment. A greater number of smaller housing units with fewer animals per pen, to allow for true replication of tested variables. Preferably, these housing pens would be randomly allocated to allow the trials to be statistically robust.

6.2.2 Further research

Housing

1 Trials comparing the performance of woodchip with a range of other bedding types besides straw, such as paper derivatives.

2 Quantify the economic cost-benefits of housing livestock indoors on woodchip, compared to out-winter pads, in relation to the N losses.

3 Further research into the absorbency potential of woodchips at differing initial moisture contents (see appendix I).

4 Investigate the pre-treatment of woodchips to increase absorbency (e.g. by crushing or change in drying regime).

5 Investigation of N transformations that occur in woodchip bedding and identification of the different factors control them (e.g. chip size, tree species, urine loading etc).

6 Behavioural responses of sheep and cattle to differing feed types, including wastage and manure volumes.

7 Investigate human and animal pathogen persistence in a wide range of bedding types e.g. wood (chips, shavings, sawdust); paper (pulp, shredded, recycled); varieties of crop residues (wheat, barley, corn, rice) and recycled composted waste (municipal waste, biosolids, farmyard manure), as well as abiotic beddings (sand, flint, rubber) etc.

Composting

8 Undertake replicated trials to cross compare the effects of different dietary inputs and differing pre-bedding moisture contents on the woodchip's composting performance over a longer timescale, e.g. 5 years.

9 Identify the extent to which compost structure (windrow vs. pyramid), and the frequency and timing of turning, control N losses during composting.

10 Investigate the effect of using labile, absorbent additions to control N losses on bedding performance, its subsequent composting and fertility value (e.g. co-bedding and co-composting with paper).

11 Determination of organic N mineralisation rates in woodchip composts, particularly low molecular weight DON, which represents an important source of N for microorganisms and some plants.

Land spreading

12 From barn to field: the persistence of steroid hormones [^{14}C] 17β-estradiol and [^{14}C] testosterone via differing pathways. Do livestock sex hormones survive from housing, through composting or slurry storage, to reach the field in sufficient concentrations to risk polluting neighbouring watercourses via seepage? (see Appendix V)

13 Carbon sequestration / storage in soil – is there agronomic value in bio-charring the soiled bedding and then ploughing it into the soil each autumn?

14 Identify fertiliser replacement rates from woodchip-manure composts of different ages.

15 A dedicated study of N balances throughout the woodchip bedding, composting and land spreading continuum.

16 Extensive greenhouse and field trials to establish fertility value of a wide range of composted livestock beddings with emphasis on other nutrients (e.g. micronutrients not included in these trials).

General

17 Social survey of farmers' attitudes to different bedding types.

18 On-farm feedstock evaluation – assist individual farmers to maximise the potential of various bedding resources they have on-farm, or otherwise make informed decisions on external sourcing of materials they could use for bedding.

APPENDIX I

A1 Woodchip water absorbency

Two experiments were carried out to determine the water absorbance characteristics of woodchips. The first aimed to establish the water absorbency rate and water holding capacity of woodchips containing different initial moisture contents (50 %, 40 %, 30 %, 20 %, 0 % and forced air dried (FAd), 6.89 %). The second experiment involved measurement of the water penetration drop time (WPDT; Letey, 1969) to characterise the degree of surface hydrophobicity in woodchips with differing moisture contents (50 %, 40 %, 30 %, 20 %, 0 % and naturally air dried (NAd) 14.5 %.

A1a: Experiment 1 - Sample preparation

To establish a homogenous moisture content in all the woodchip used in this experiment, approximately 2 kg of ADAS W34 raw bedding was rinsed with water, placed in pre-weighed aluminium foil trays and forced air dried at 30 ± 2° C in a fan-assisted oven for 17 d, until constant weight had been achieved. The woodchips were then thoroughly mixed before being divided into eighteen replicate batches, sealed in air-tight plastic bags and labelled with their weights. Fifteen of these were subsequently stored at 4° C, while the remaining three were oven dried at 80° C for 3 d to determine their initial moisture content. These oven-dried samples were retained and used as the replicate batches of woodchip containing 0 % moisture. Three of the fifteen bags were further randomly selected and labelled FAd (forced air dried) 6.89. The remaining 12 samples were placed in nylon mesh and fully immersed in tap water for 100 h to allow the woodchips to reach their water holding capacity. The bags were then removed from the water and allowed to drain until no further water loss was seen. The water saturated chips were then placed in aluminium foil trays, placed in a 30° C fan-assisted oven and allowed to dry until moisture contents of 50, 40, 30 and 20 % had been achieved. This was achieved after drying times of 8, 12, 14 and 16 d respectively. The chips were then weighed, labelled and stored in sealed plastic bags at 4° C. Table 1 shows the mean moisture contents achieved for each increment group.

Table A1.1: Target and actual moisture contents in the woodchips used in the experiments. Values represent means ± SEM (*n* = 3).

Target moisture content (%)	Actual moisture content (%)
50	50.3 ± 0.1
40	40.2 ± 0.1
30	30.2 ± 0.1
20	20.3 ± 0.1

Replicate samples of woodchips with the differing water contents (50, 40, 30, 20, 6.89 and 0 %; $n = 3$) were submerged in tap water and their weight gains recorded after 1 hour, 1 day and 1 week.
The amount of water sorption over time is shown in Figure A1.1.

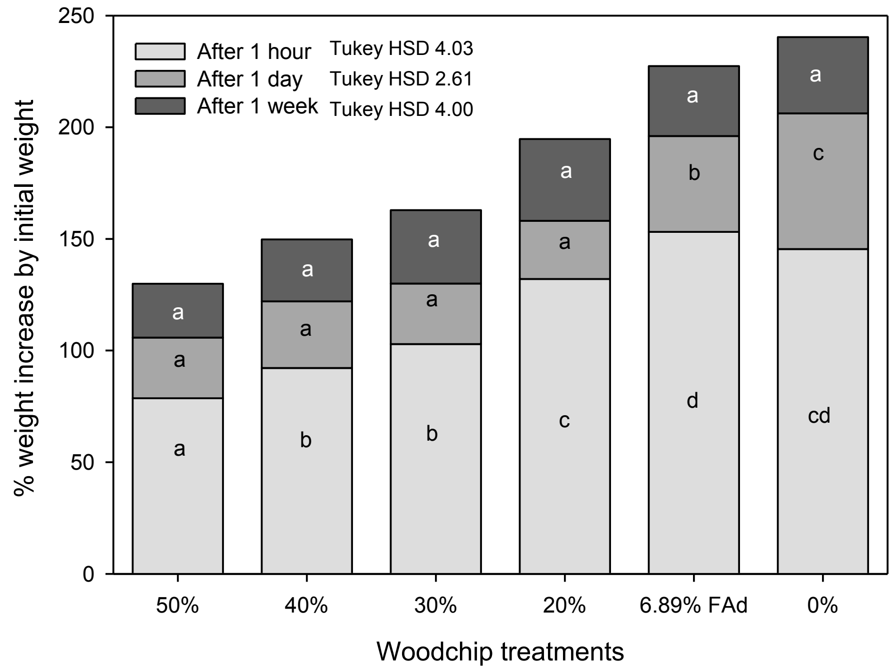
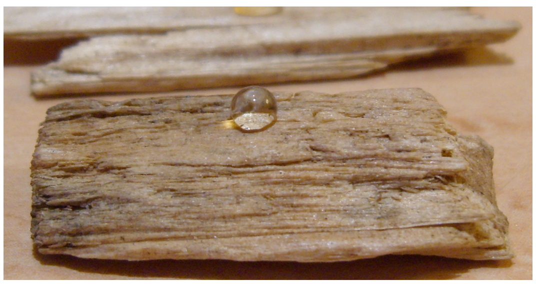


Figure A1.1: *Absorbency rate and capacity of woodchips with different initial moisture contents. Each column increment represents the percentage weight increase with the time period based on the initial mean weight of the treatment. Letters a, b, c, and d within each column increment represent significant (p<0.05) differences between treatments.*

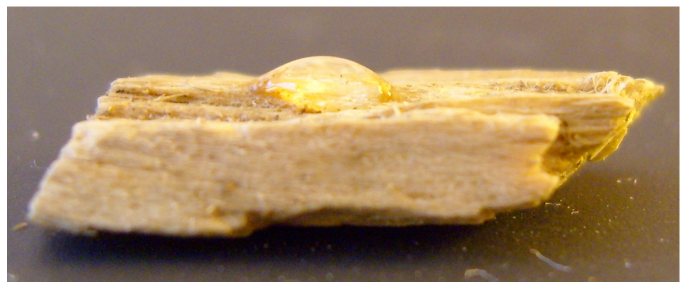
Woodchip's capacity to absorb moisture is fundamental to its usefulness as a livestock bedding material. The key parameters are the speed (rate) with which it is able to absorb moisture and the quantity of moisture it is able to absorb (capacity). Figure A1.1 shows that during the first hour of wetting, woodchips with low initial moisture contents absorb significantly more moisture at a faster rate than those with higher initial moisture contents. The maximal rate of absorption was achieved by the FAd treatment 6.89 % initial MC, beyond which the absorbency rate becomes limited by hydrophobicity. However, this level of desiccation would be unobtainable in most conventional farm scenarios.

A1b: Experiment 2 - Water Drop Penetration Time (WDPT)

The WDPT test was developed by Letey (1969) and measures the time that hydrophobicity persists on a porous surface. A drop of water is placed on a woodchip surface and the time taken for the liquid to penetrate the matrix is recorded. If the drop does not penetrate immediately, it indicates that the water surface tension is above that of the wood and woodchip surface. This is identified by the water contact angle being greater than or equal to 90°. The WDPT measures the stability of water repellency (Doerr, 1998), which is an important determinant of factors such as soil surface run-off. Letey et al. (2000) recognised that, owing to the radius of some pores being greater than the droplet radius, part of the droplet might disappear even when the liquid to surface contact angle is more than 90°.



0 % replicate 1, drop 2



50 % replicate 1, drop 3

A1b.1 Sample Preparation

After drying woodchip samples in a 30° C (± 2° C) oven to achieve the required initial moisture contents of 50 %, 40 %, 30 % and 20 %, samples were placed in sealed, labelled plastic bags. The naturally air-dried 'NA-d' woodchips were taken from previously soaked woodchips that had then been hung in nylon bags in a ventilated room for 3 months prior to use (moisture content of 14.5 %).

A1b.2 Method

A standard sized (~ 0.03 ml) droplet of distilled water was pipetted on to the surface of three woodchips selected from each treatment (50 %, 40 %, 30 %, 20 %, naturally air dried (NAd) 14.5 % and 0 %) and the precise absorption time recorded. This process was repeated two more times. If penetration time exceeded 1 hour, samples were covered to avoid evaporation.

A1b.3 Results

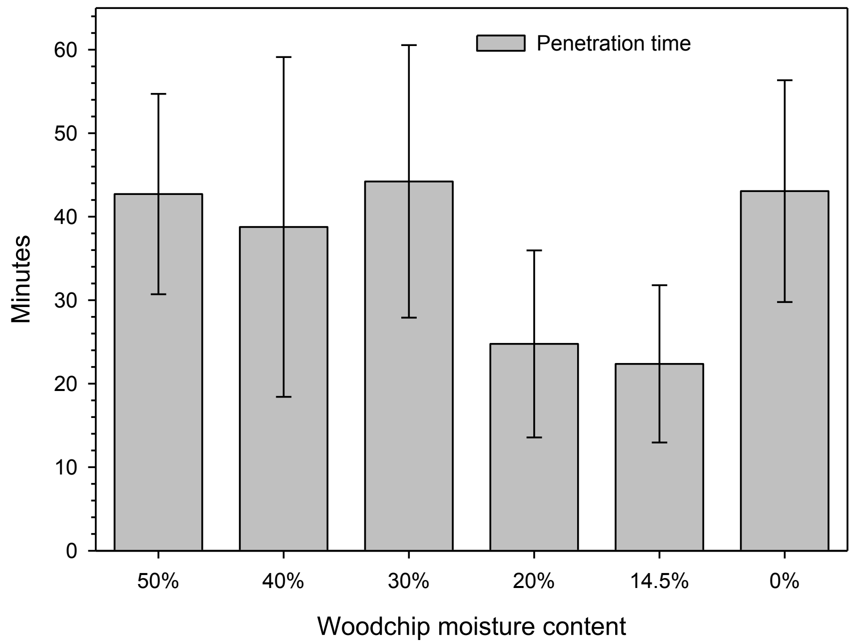


Figure A1.2: *Mean (n=9) treatment water drop penetration time, ±1 SE.*

The results in Figure A2.2 show that hydrophobicity appears to inhibit absorption to a similar extent as woodchips with high initial moisture contents. However, <5 % MC is impractical within a working agricultural scenario; as such, woodchip hydrophobicity may be considered a purely theoretical problem for Welsh farmers. However, the results do confirm that woodchip absorbency rates and capacity are dramatically enhanced in woodchips with MC that is <30 % MC and, preferably, as near to the air-dried minimum as possible.

A1 References

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APPENDIX II

Appendix – II(a) – ADAS Field trials

The application of composted woodchip-based manure to grassland.

A2a.1 Objective

To evaluate the effect of applying composted woodchip-based manure to conservation cut grassland. The demonstration had a total of 14 plots, which included plots receiving artificial N. The application rate of composted material was at a flat rate, based on manure spreading rates but not exceeding 150 kg/ha N. ADAS assessed yield and ensiling quality of grass obtained from the different composts and compared to inorganic N fertiliser. The demonstration was also designed to give an indication of how much N was locked up.

A2a.2 Treatments

14 plots, 3 m wide and 10 m long were marked out and allocated at random to one of the following treatments.

T1	Control – No Nitrogen	
T2	AN25 – 25 kg/ha N as NH_4^+ NO_3^-	
T3	AN50 – 50 kg/ha N as NH_4^+ NO_3^-	
T4	AN75 – 75 kg/ha N as NH_4^+ NO_3^-	
T5	AN100 – 100 kg/ha N as NH_4^+ NO_3^-	
T6	AN150 – 150 kg/ha N as NH_4^+ NO_3^-	
T7	Com CSt	– 15 tonne/ha as Cattle/Straw
T8	Com C20	– 15 tonne/ha as Cattle 34 % moisture
T9	Com C40	– 15 tonne/ha as Cattle 53 % moisture
T10	Com C60	– 15 tonne/ha as Cattle 55 % moisture
T11	Com SSt	– 15 tonne/ha as Sheep/Straw
T12	Com S20	– 15 tonne/ha as Sheep 34 % moisture
T13	Com S40	– 15 tonne/ha as Sheep 53 % moisture
T14	Com S60	– 15 tonne/ha as Sheep 55 % moisture

A2a.3 Materials and methods

A2a.3.1 Soil analysis

Preliminary soil samples (0 – 7.5 cm depth) were collected winter / spring 2007 and analysed for P and K status. Appropriate applications of P and K were added to achieve soil indices of 3 for phosphate and 3 for potash (RB209) so that these were not limiting during the experiment. Immediately prior to fertiliser / compost application, soils were collected and assessed for pH P and K status. Subsamples of compost were stored under cover in ½ tonne dumpy bags over the winter of 2006/07. Samples were analysed for N content and used to calculated the N / ha.

Plots were 3 m wide and 10 m long. Plots were marked out in grassland used for silage making. Fields were then closed for silage in mid-May. Composts were applied evenly to the whole area of the plots. Artificial fertiliser (ammonium nitrate @ 34.5 % N) was applied by hand to ensure an even application onto the surface of the plots. Half of each plot (5 m x 2.4 m) was harvested in mid-July a day or two prior to the woodchip open day. Dry matter yields and estimates of silage quality of the forage from each plot was assessed and made available for presentation at the open day. The other half of each plot was left uncut to demonstrate grass growth.

A2a.4 Results

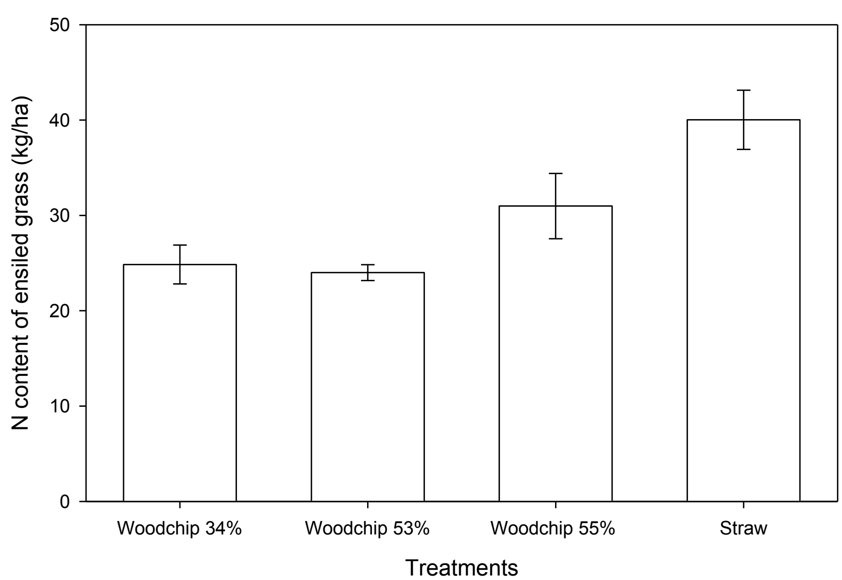

Figure A2.1: *Comparison of ensiled grass N contents harvested from the ADAS trial. Partner sheep and cattle bedding composts are combined.*

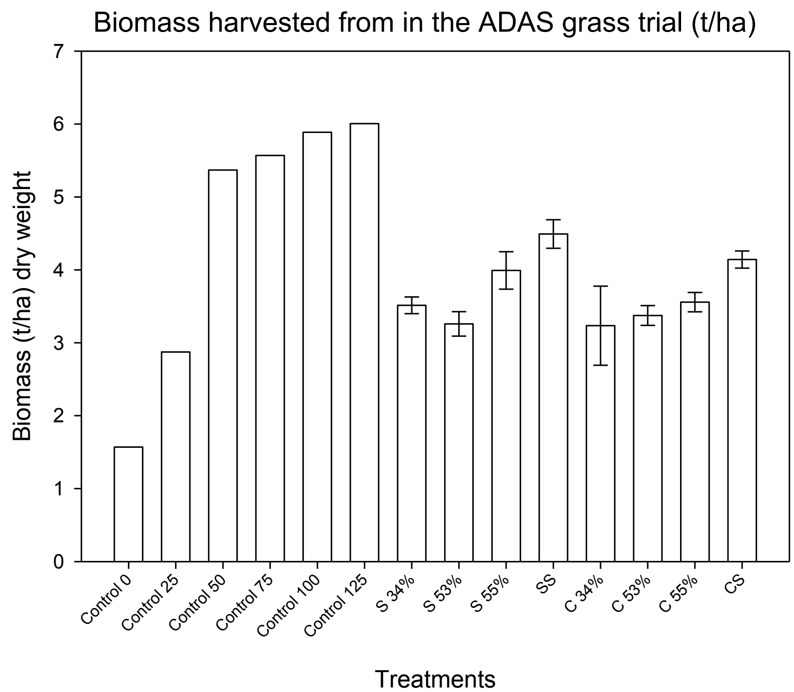

Figure A2.2: *ADAS's grass trial biomass yields (t/ha). ± SE is not included for inorganic N treatments as ADAS did not provide data replicates.*

Composted treatments were applied at the equivalent to 15 t ha^{-1}. Compost N content was not determined. However, using IGER's application rate as a guide, it appears the composted amendments underperformed compared to biomass produced from the equivalent rate of artificial N. Woodchip compost yields are also lower than their straw-based counterparts.

Appendix – II(b) – IGER Field trials

A demonstration evaluating the effect of compost derived from different husbandry practises on the yield of spring barley.

A2b.1 Objective

A demonstration was conducted to evaluate the effect of applying compost derived from dairy heifers or sheep, bedded on straw or woodchip and fed either hay or silage. The application rate of composts was based on their % N content and compared with plots receiving artificial N. The demonstration assessed the yield of barley forage and barley grain obtained from the different composts and compared to inorganic N fertiliser.

A2b.2 Treatments

13 plots, 3 m wide and 10 m long were marked out and allocated at random to one of the following treatments.

T1	Control – No Nitrogen	
T2	AN25 – 25 kg/ha N as NH_4 NO_3	
T3	AN50 – 50 kg/ha N as NH_4 NO_3	
T4	AN75 – 75 kg/ha N as NH_4 NO_3	
T5	AN100 – 100 kg/ha N as NH_4 NO_3	
T6	Com CSH	– 75 kg/ha N as Cattle/Straw/Hay Compost
T7	Com CSS	– 75 kg/ha N as Cattle/Straw/Silage Compost
T8	Com CWH	– 75 kg/ha N as Cattle/Woodchip/Hay Compost
T9	Com CWS	– 75 kg/ha N as Cattle/Woodchip/Silage Compost
T10	Com SSH	– 75 kg/ha N as Sheep/Straw/Hay Compost
T11	Com SSS	– 75 kg/ha N as Sheep/Straw/Silage Compost
T12	Com SWH	– 75 kg/ha N as Sheep/Woodchip/Hay Compost
T13	Com SWS	– 75 kg/ha N as Sheep/Woodchip/Silage Compost

A2b.3 Materials and methods

A2b.3.1 Soil analysis

Preliminary soil samples (0 – 7.5 cm depth) were collected during winter/spring 2007 and analysed for P and K status. Appropriate applications of P and K were added to achieve soil indices of 3 for phosphate and 3 for potash (RB209) so that these were not limiting during the experiment. Immediately prior to fertiliser / compost application, soils were collected and assessed for pH P and K status. Subsamples of compost were stored under cover in ½ tonne dumpy bags over the winter of 2006 / 07. Samples of the compost were analysed for % N content and used to calculated the rate required to achieve 75 kg N / ha.

Plots were 3 m wide and 10 m long. Composts were applied evenly to the whole area of the plots. Artificial fertiliser (ammonium nitrate @ 34.5 % N) was applied by hand to ensure an even application onto the surface of the plots. Plots were ploughed to a depth of 100 mm and power harrowed in preparation for sowing. Spring barley (cv *Riviera*) was drilled at a rate of 185 kg / ha to establish a 10 m by 2.4 m plot and rolled. Half of each plot (5 m x 2.4 m) was harvested as whole-crop in mid-May, a day or two prior to the wood chip open day. Dry matter yields and nitrogen content of the forage from each plot was assessed and made available for presentation at the open day. The other half of each plot was harvested as dry grain in August, after which grain yield and nitrogen content was assessed.

Plate A2.1: IGER's CSC and CHC Barley Riviera field trial plots demonstrated at the IGER open day in mid-May 2007.

Table A2.1: shows % N (determined by IGER) in each treatment compost, the application rate required to achieve 75 kg N / ha and the actually mass applied.

Treatment	% N	Compost tonnes (75 kg N ha^{-1})	Compost kg (30 m^2 plot)
SSS	1.72	4.37	13.1
SSC	0.74	10.1	30.3
SHS	1.16	6.45	19.3
SHC	0.68	11.0	32.9
CSS	1.49	5.02	15.1
CSC	0.46	16.3	48.9
CHS	1.16	6.45	19.4
CHC	0.42	17.7	53.0

A2b.4 Results

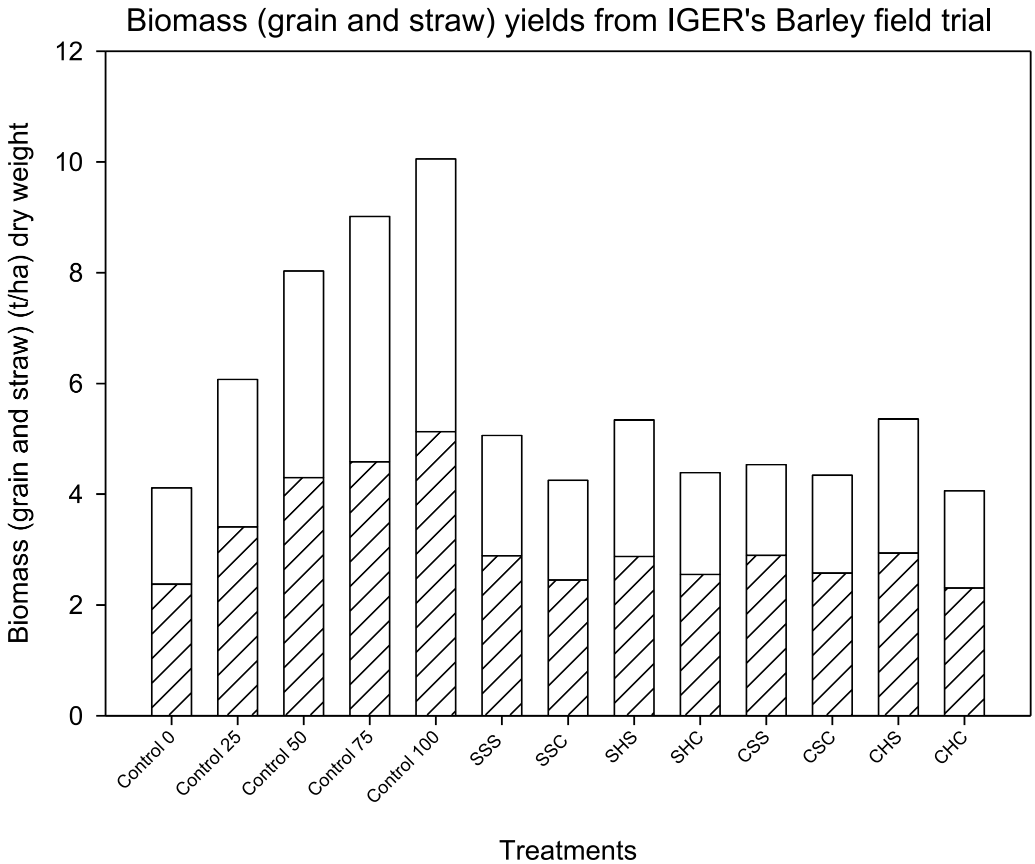

Figure A2.3: *IGER's barley field trial yields (t/ha); biomass (entire bar); grain (hashed bar section); straw (white bar section). ± SE is not included as IGER did not provide data for replicates. Inorganic N treatment codes are displayed as Control #; determined by the applied rate kg/ha. Compost treatment codes are displayed by Livestock/Feed/Bedding e.g. Sheep Silage Chip, SSC.*

At percentage N application rates, biomass from the composted treatments is below that produced by inorganic N at the equivalent rate (75 kg N ha^{-1}) and woodchip-based treatment yields are also lower than each equivalent straw-based treatment, but the difference in biomass between straw and woodchip amendments was not as great as shown in pot trials.

APPENDIX III

Appendix – III – Compost Markets: End use options for woodchip/manure compost

A3.1 Aim

To investigate potential markets for composted woodchips in agronomic, horticultural and industrial settings, with an objective to establish and validate markets.

A3.2 Introduction

The opportunities to establish commercial 'end use' markets for woodchip/manure (WM) compost are hindered by a number of processing factors:

- Legislatively, the lesser volume of compost produced the better – a full waste management license is needed if a farmer's on-site operating volume (including bedding in use, part and finished compost) is >1000 m^3. However, it is expected that average individual farm-scale production volumes and infrequency of supply will economically exclude farmers from securing large or long-term contracts with local authorities and the biomass/industrial sector, when competing with green waste producers.

- In addition to the prohibitive licensing and regulatory costs associated with producing commercial WM compost at farm-scale, there are a range of novel factors affecting its standardized production:

    - Pre-bedding moisture content – percentage H_2O
    - Type of livestock manure – sheep or cattle
    - Wood type – hardwood or softwood
    - Livestock feed – hay or silage
    - Quantity of woodchip used – ratio of woodchip to manure in compost
    - Weather – outdoor composting only
    - Management – turning regime, compost location, watering etc.

The influence of these variables in unique combinations causes irregular decomposition rates and chemical composition, and thus variations in the final compost value.

The single most critical factor in producing WM compost for on-farm use is the woodchip's pre-bedding moisture content; it is considered that with > 30 % H_2O content, the woodchip will not absorb sufficient N-rich liquid excrement to fuel the required level of early microbial metabolic activity, needed to satisfy the PAS 100 temperature requirements of 65^{O} C for 7 days, in conjunction with maintaining compost moisture levels and a strict monthly turning protocol.

The following schematic diagram identifies a range of possible end uses for WM compost.

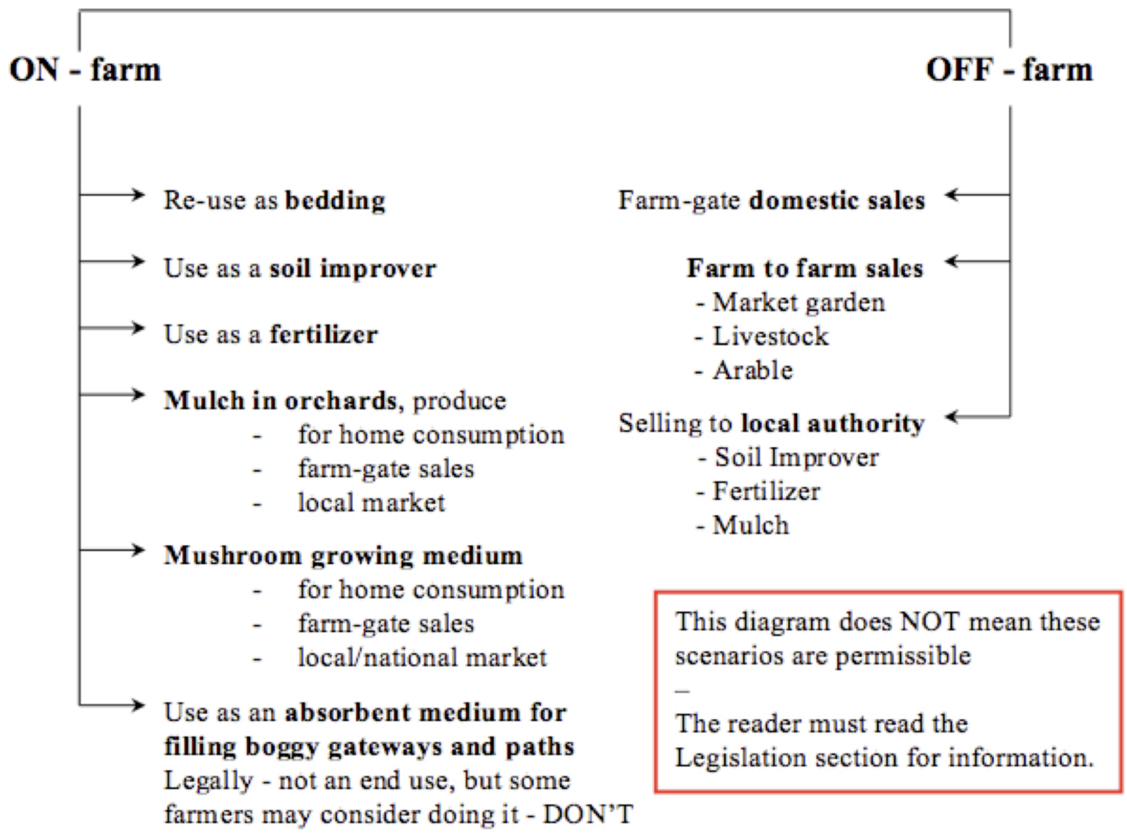

Figure A3.1: *Possible end uses for WM compost.*

A3.2.1 Glossary

PAS 100: PAS 100 is a processing standard that itemises the allowable source-segregated feedstocks, monitoring, output testing requirements for composts and permitted levels of contaminants.
COGAP: Code of Good Agricultural Practice
WMLR: Waste Management Licensing Regulations 1994 (as amended No.3 Regs 2005)

A3.2.2 Legislation

The regulations surrounding the sourcing, use and sale of WM compost are complex. However, there are some solid markers to help us navigate the finer points.

Firstly, an overriding requirement for a waste activity to be exempt from licence is that the waste must be recovered or disposed of without endangering human health and without using processes or methods that could harm the environment. Specifically, such processes should be carried out without:

- Risk to water, air, soil, plants or animals
- Causing nuisance through noise or odours
- Adversely affecting the countryside or places of special interest

If this overriding requirement, or any one of the specific limitations, is unlikely to be met then a waste management licence will be required.

The scenarios in this report focus on regulations specific to 'end-use' options. However, the regulations regarding the sourcing and composting of WM are the same in almost all cases; to avoid repetition they are listed here:

- If the woodchip comes from a waste source e.g. pallets, exemption (under paragraph 15 of schedule 3, WMLR 1994) must be registered to use the woodchip – ALL scenarios.

- Compost storage, transportation and application to land are controlled by the WMLR; exemptions permit compost and some uncomposted wastes to be spread to land for agricultural benefit under paragraph 7a of schedule 3 - WMLR – scenarios 2 4 5 7 8 9.

- Composting of <1000 m^3 can be registered exempt under paragraph 12, schedule 3 WMLR, but >1000 m^3 requires a Waste Management license – ALL scenarios.

- A paragraph 12 exemption must be registered to compost the woodchip. The EA is reluctant to grant a paragraph 12 exemption where the proposed site is within 250 m of a 'receptor' (housing, places of work, public rights of way, livestock etc.), due to concern over bio-aerosols – there are smaller limits dependent on the volume and type of compost, operating methods, prevailing wind and risk management provisions. This is in the Interim Internal Guidance on Composting. – ALL scenarios

- The compost must meet the COGAP requirements – ALL scenarios:

    - Run-off from field heaps does not cause water pollution.
    - Run-off from stores on concrete bases should be collected and contained.
    - Poultry manure stored outside must be in narrow A-shaped heaps to shed rainwater.

- Compost that is Quality Protocol certified (which includes the PAS 100 standard) can be sold and moved without license. Otherwise, it is considered 'waste' – ALL scenarios.

A3.3 Scenarios

The following scenarios are listed in the same order as in the diagram above, starting with ON-farm activities. The regulatory information herein was gathered with the help of Sarah Aubrey (Environment Agency), Les Eckford (Animal Health) and Gavin Watkins (VLA).

1. Re-using WM compost as a bedding the following year

Woodchip compost can be re-used as bedding so long as the following conditions are satisfied.

- It meets PAS 100 composting standards and therefore does not endanger human, animal or environmental health.

- **And** *'the animals have dry areas to lie down'* (Schedule 1 of the Welfare of Farmed Livestock (Wales) Regulations 2007, paragraphs 13 and 17 in particular) – if the compost has met PAS 100 temperature requirements it is reasonable to expect the moisture content will be sufficiently low to provide dry bedding the following winter.

- **And** '*the composted woodchip does not contain high levels of dust, noxious gases or spores etc.'* – after 7 months' composting there should be no noxious gases, but depending on the compost's novel factors (listed in the introduction) precautionary analysis of dust and spores may need to be carried out.

2. Using part or fully finished WM compost in years 1, 2 or 3 as a soil improver

Full or part-finished WM compost can be used as a soil improver. It does not have to reach PAS 100. However, if has not, it must not leave the site of production, **and** part-finished compost must be fully ploughed in, as large chunks of woodchip on the soil surface could be classified as waste disposal. The agric-waste exemption paragraph 7A allows up to 50 t/ha (based on nutrient requirements). Exemptions are issued free of charge, if the compost is spread on the farm that produced the waste.

Spreading must meet COGAP requirements;

- 10 metres from a watercourse
- 50 metres from a spring well or borehole
- No spreading on waterlogged ground
- No spreading on steep slopes
- No spreading on frozen land – frozen for 12 hrs or more in a 24 hr period.

3. Using finished WM compost as a grassland or cereal fertiliser

This presents no problem: the regulations are the same as above.

4. Using WM compost in years 1, 2 or 3 as a weed-disease control, tree mulch in orchards, which results in produce:

a. For home consumption only
b. For farm-gate sales or supply to a local market

Must be registered exempt under paragraph 7 and paragraph 12; the mulch itself must be used on the same site it is produced and cannot be sold to market unless composted to PAS 100 standard in which case it can fall under the WRAP Quality Protocol, as materials exempt in paragraph 12 are still not allowed off site.

There are no problems with selling produce grown in or from WM compost.

5. Using WM compost in years 1, 2 or 3 as a mushroom growing medium, resulting in produce:

a. For home consumption only
b. For farm-gate sales or supply to a local or national market

Providing the mushrooms are grown at the site of compost production, regulations are the same as the above, except that the volume of compost allowed on site of production at any one time is <10000 m^3 before the producer needs a full licence.

In 2004/05, ADAS Pwllpeiran was commissioned to conduct a series of trials, using WM compost as an organic mushroom growing medium. The 2004 trial results found that, of the 4 varieties of mushroom trialled, only oyster mushrooms bore fruiting bodies and concluded that further work was needed. In 2005 a follow-on trial was carried out using 6 varieties of mushrooms and concluded that the '*commercial possibilities of cultivating varieties of edible fungi on woodchip-based and other substrates has yet to be demonstrated*.'

The report went on to say, '*At present, the potential for outdoor exotic mushroom growing in Wales is likely to be limited to small-scale growing of oyster mushrooms or shiitake on oak logs. These systems can provide additional on-farm enterprises for farms wishing to diversify and to supply local markets, but harvest period and yield is likely to be erratic and dependent on weather and seasonal conditions.*' (ADAS, 2005-2006).

Using WM compost as an absorbent medium for filling in boggy gateways or paths;

a. Using raw un-composted woodchip bedding straight from the barn
b. Using ‘PAS100 temperature sanitized’ 1st yr WM compost

Not allowed. This material is not listed as exempt under paragraph 19 and this activity carries a high risk of pollution.

*NB: Orchard fruits and mushroom growing are highlighted here, but organic farmyard manure can be use to produce all horticultural products, for either home or commercial consumption.

However, depending on the source of the woodchip, high metal content/PTE - Potentially Toxic Elements analysis may be needed. For example, chipped pallets are likely to be high risk and compost analysis must be carried out to ensure no detriment to humans, land or livestock.

The next set of scenarios looks at the sale of WM compost, again with just a key point summary for each scenario outlining the laws and regulations surrounding the sale of WM compost and the responsibilities of the seller and buyer when moving it off-farm.

6. Farm-gate domestic sales of ‘PAS100 temperature sanitized’ WM compost

E.g., would a gardener need a waste movement license to buy compost for their roses?

The PAS 100 compost remains a ‘waste’ (and therefore operating volume on-site must remain <1000 m3) until it is moved off the site of production, whereupon it can be treated as a product, but as an agric-waste, it must comply with the Quality Protocol. Therefore, a buyer/gardener would not need a license, but the QP requires the seller to keep track of where the compost has gone.

QP certification is quite complicated, and costs £2000+ (lab and certification costs), so it is only worthwhile if production volumes are large, or if a number of farms form a collective.

Therefore, while there is no limit to the amount of PAS 100 finished compost that can be stored off site, the production volume on site will still be limited to 1000 m^3 per farm at any one time. As a guide, a farmer housing 200 ewes over winter would produce roughly 40-50 m^3.

7. Farm to farm sales:

a. Livestock farmer supplying composted manure to a market gardener.
b. Livestock farmer supplying composted manure to another organic livestock farmer

Regulations are the same as above.

8. Selling the WM compost to the local authority:

a. As mulch e.g. for roundabouts
b. As a soil improver
c. As a fertiliser

It is anticipated the volumes produced by the majority of sole trading livestock farmers will be insufficient for LA requirements.

A3.4 Summary

It is considered that, for the majority of farm-scale operations, the end use options for mature WM compost will be economically confined to on-farm use, unless farmers form a collective, which would enable them to produce WM at sufficient economies of scale by spreading the costs of certification and machinery, while benefiting from each partner's volume allowance.

However, the volume and performance of existing green waste available to large-scale end users such as LAs and industrial consumers, significantly undermines the need for, and so demand for, bulk production of WM compost.

A3.5 Acknowledgements

Sarah Aubrey, Environment Agency.

Les Eckford, SRD – OCVO, Animal by-products / welfare / exotic disease.

Gavin Watkins, Regional Veterinary Manager, VLA.

A3.6 References

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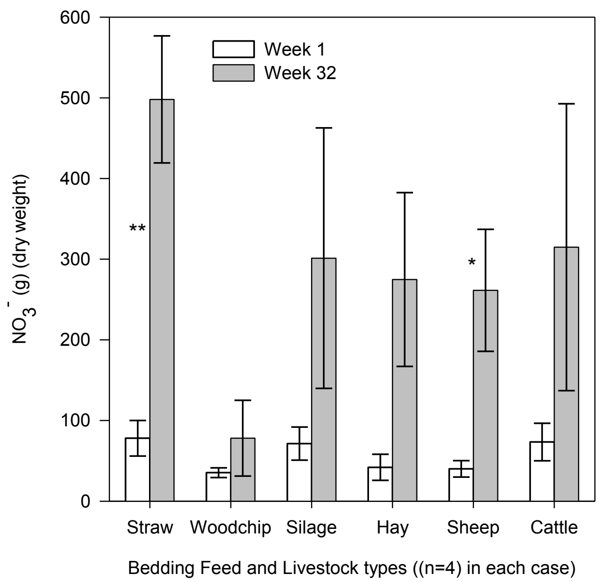
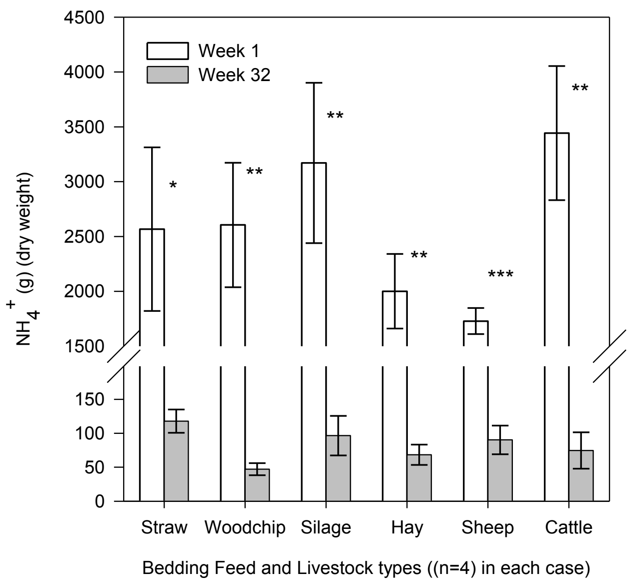
Organic Centre Wales, UWA under Farming Connect, 2004. The use of composted woodchip as a substrate for growing varieties of edible mushrooms. Available at:
http://orgprints.org/10864/01/woodchip_mushroom_trial_2004.pdf

APPENDIX IV

APPENDIX – IV – Change in total mass of nutrients at IGER

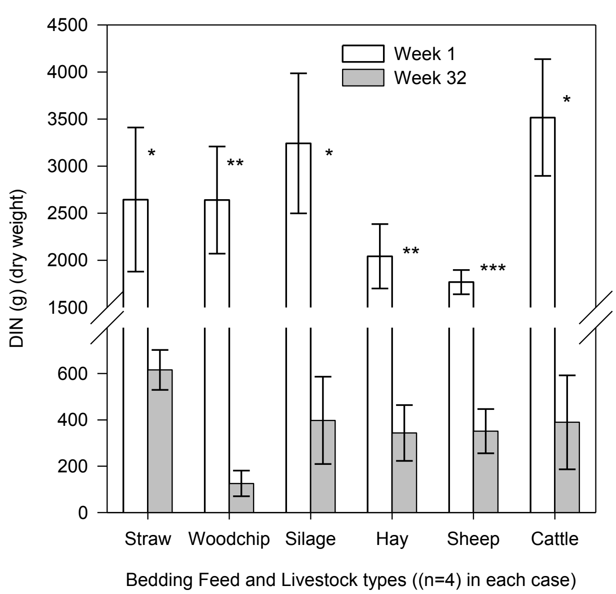
A4.1 Nitrate (NO_3^-) and Ammonium (NH_4^+)

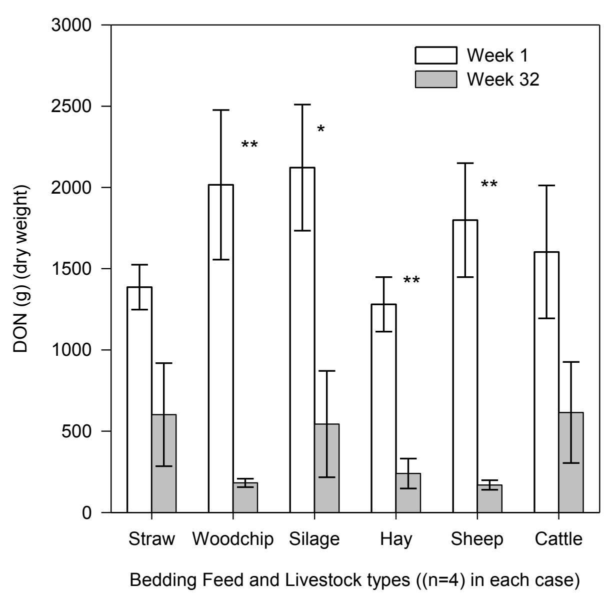




Figures A4.1 (NO_3^-) and A4.2 (NH_4^+): *show total mass of nitrate and ammonium in compost treatments at week 1 (white bars) and week 32 (grey bars). Error bars represent ±1 SE. Symbols displayed above treatment columns represent significant (* $p<0.05$; ** $p<0.01$ and *** $p<0.001$) changes in mass.*

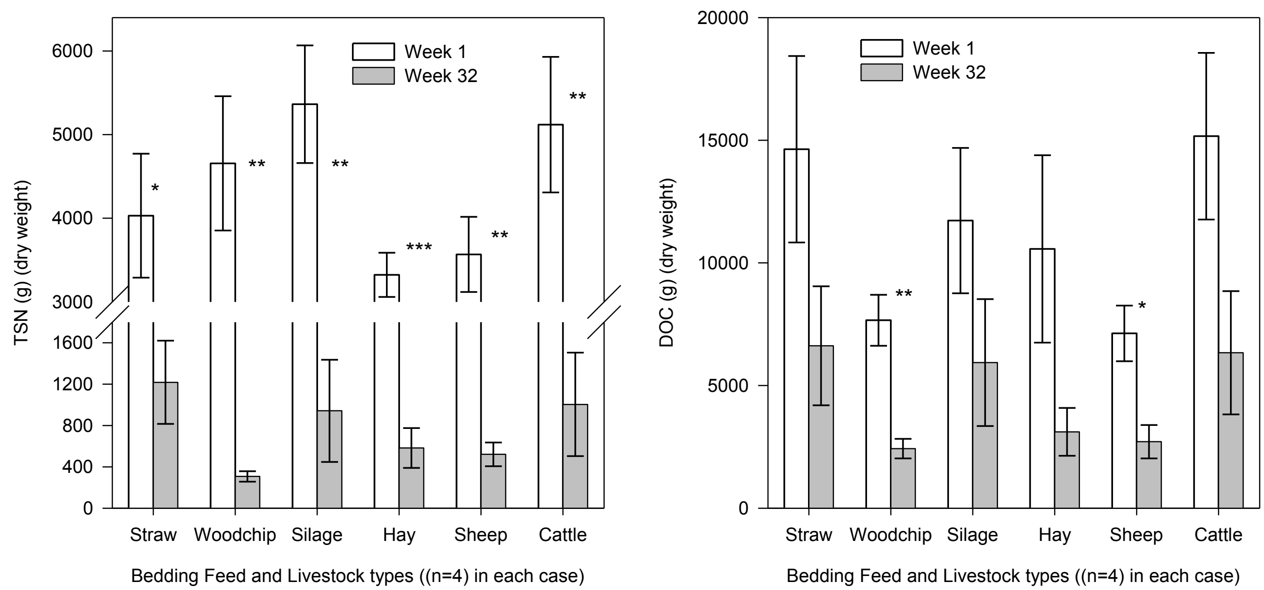
A4.2 Dissolved inorganic nitrogen (DIN) and dissolved organic nitrogen (DON)





Figures A4.3 (DIN) and A4.4 (DON): *show total mass of DIN and DON in compost treatments at week 1 (white bars) and week 32 (grey bars). Error bars represent ±1 SE. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in mass.*

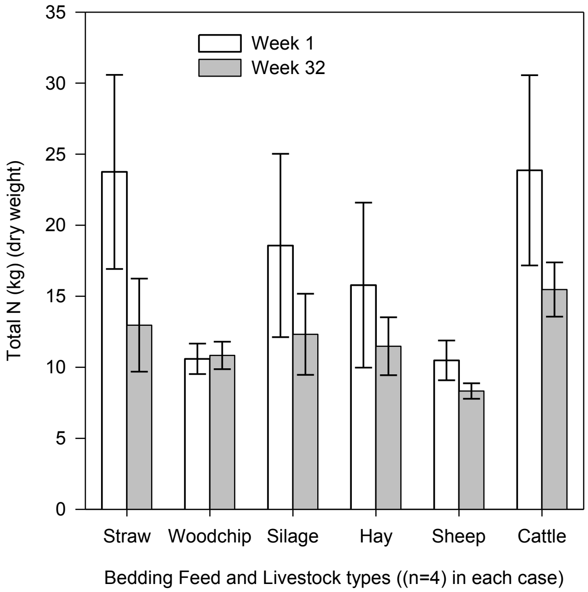
A4.3 Total soluble nitrogen (TSN) and dissolved organic carbon (DOC)

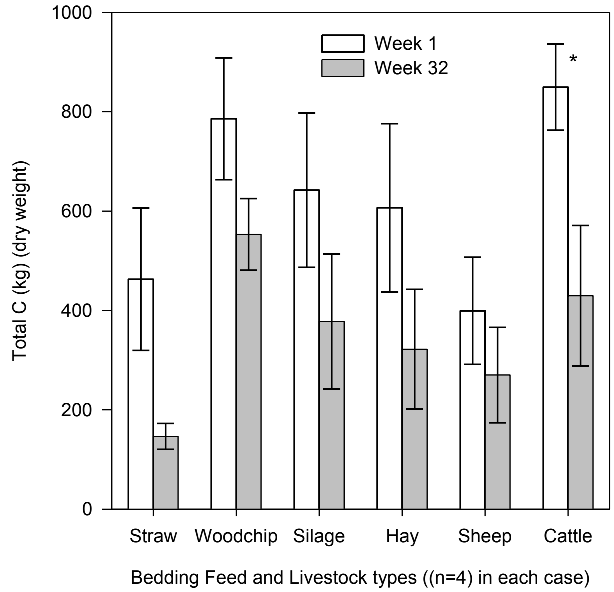


Figures A4.5 (TSN) and A4.6 (DOC): *show total mass of TSN and DOC in compost treatments at week 1 (white bars) and week 32 (grey bars). Error bars represent ±1 SE. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in mass.*

DOC in woodchip composts fell by 68 % and TSN by 92 % compared to decreases in straw treatments of 56 % (DOC) and 72 % (TSN). DOC losses were greater in hay (68 %) than silage (55 %) treatments, although TSN (82 %) loss was the same in both feed treatments. Sheep and cattle treatments varied the least, where DOC and TSN in sheep treatments fell by 63 % and 84 %, while in cattle composts they fell by 61 % and 80 % respectively.

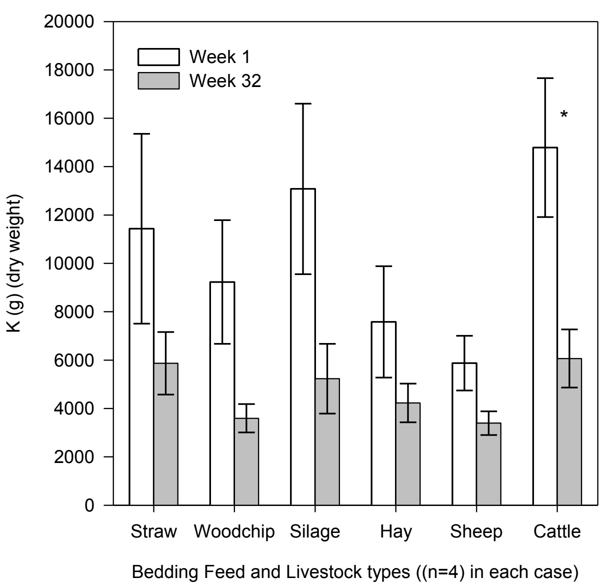
A4.4 Total nitrogen (TN) and total carbon (TC)

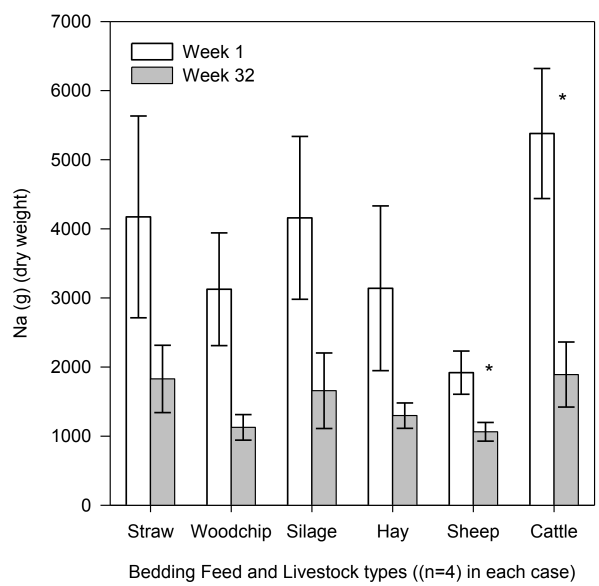




Figures A4.7 (TN) and A4.8 (TC): *show total mass of TN and TC in compost treatments at week 1 (white bars) and week 32 (grey bars). Error bars represent ±1 SE. Symbols displayed above treatment columns represent significant (* $p<0.05$; ** $p<0.01$ and *** $p<0.001$) changes in mass.*

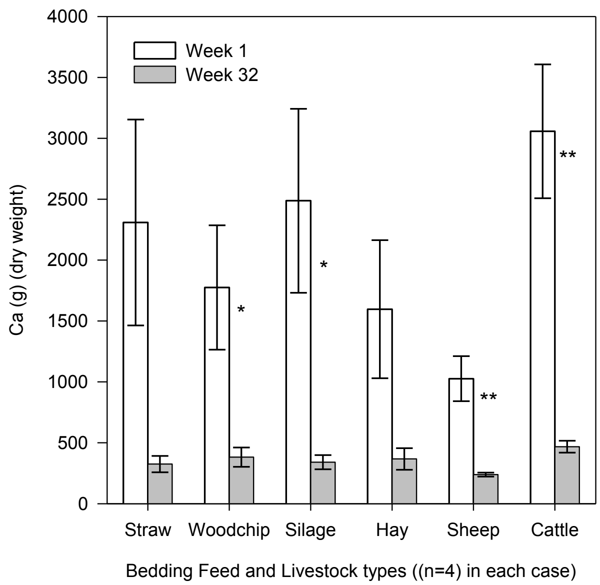
A4.5 Potassium (K_2O) and Sodium (Na)

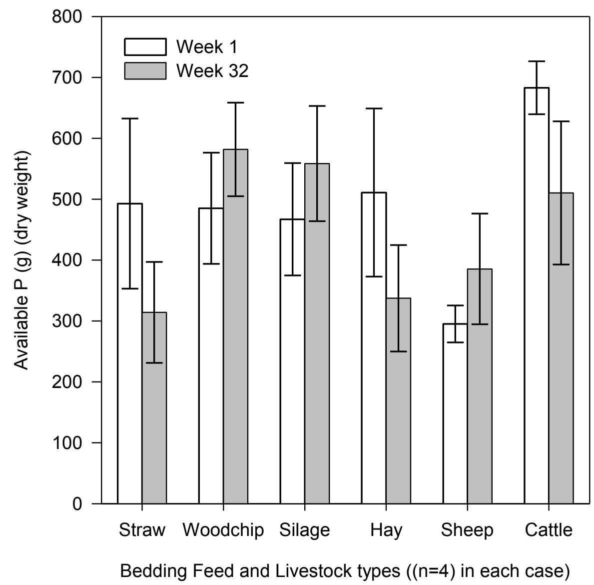




Figures A4.9 (K) and A4.10 (Na): show total mass of potassium and sodium in compost treatments at week 1 (white bars) and week 32 (grey bars). Error bars represent ±1 SE. Symbols displayed above treatment columns represent significant (p<0.05; ** p<0.01 and *** p<0.001) changes in mass.*

A4.6 Calcium (Ca) and soluble P (P_2O_5)





***Figures A4.11 (Ca) and A4.12 (P):** show total mass of calcium and soluble P in compost treatments at week 1 (white bars) and week 32 (grey bars). Error bars represent ±1 SE. Symbols displayed above treatment columns represent significant (* p<0.05; ** p<0.01 and *** p<0.001) changes in mass.*

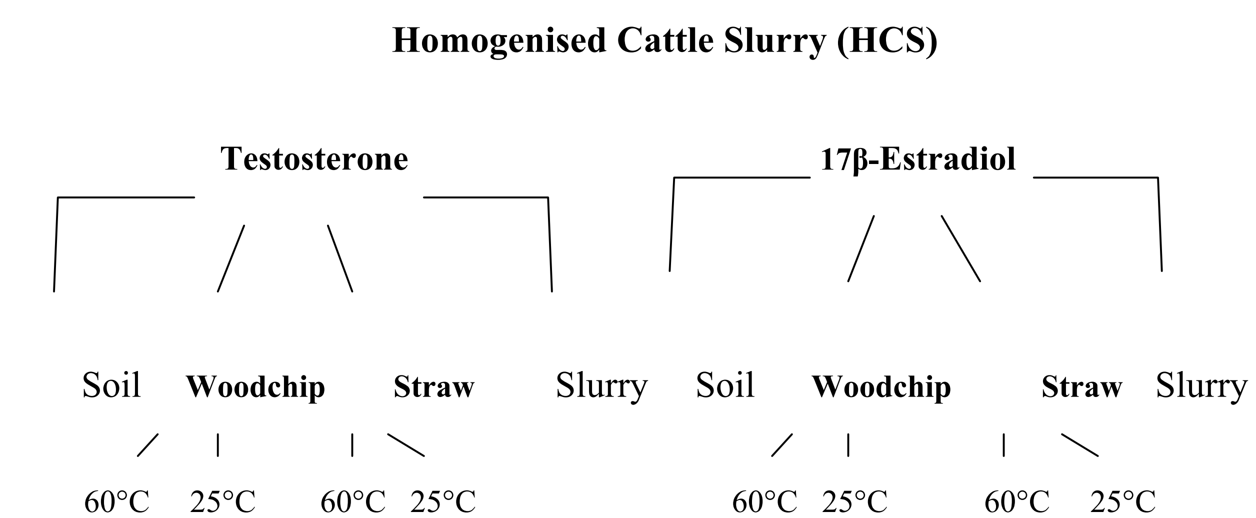
APPENDIX V

Appendix – V – From Barn to Field; the persistence of steroid hormones [^{14}C]17β-estradiol and [^{14}C]testosterone via differing pathways.

The following is preliminary work conducted in preparation, although technical difficulties prevented completion of the experiment within the time available.

A5.1 Hypotheses

1. The inclusion of a manure management phase - i.e. slurry storage, active (60° C) or static (25° C) composting - will lessen the levels of endocrine disrupting hormones 17β-estradiol (E) and testosterone (T) being applied to agricultural land and, thereafter, potentially entering surrounding watercourses via leaching.
2. Composted manure/bedding treatments will degrade/deactivate a greater amount of steroids than slurry storage.
3. Active (60° C) composting will degrade/deactivate a greater amount of steroids than static (25 °C) composting.
4. Active woodchip-manure composts will degrade/deactivate a greater amount of steroids than straw-manure composts.



A5.2 Treatments and Replicates

Testosterone (T)

Soil + Slurry + T

Slurry (aged, active or static?) + T

Straw + Slurry + T composted at 60° C (temperature ramp profile)

Straw + Slurry + T composted at 25° C

Woodchip + Slurry + T composted at 60° C (temperature ramp profile)

Woodchip + Slurry + T composted at 25° C

17β-estradiol (E)

Soil + Slurry + E

Slurry (aged, active or static?) + E

Straw + Slurry + E composted at 60° C (temperature ramp profile)

Straw + Slurry + E composted at 25° C

Woodchip + Slurry + E composted at 60° C (temperature ramp profile)

Woodchip + Slurry + E composted at 25° C

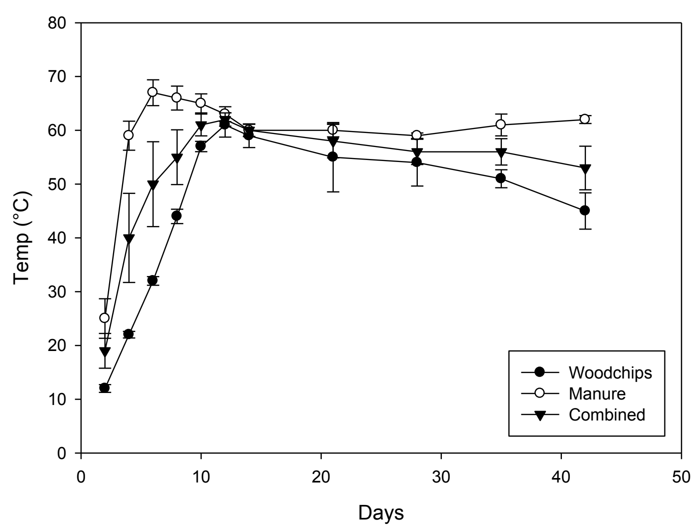
ALL TREATMENTS HAVE 3 REPLICATES **N = 36**

A5.3 Treatments

Rep	Testosterone	CODE	Rep	Estradiol	CODE
1	Slurry+T	ST **1**	1	Slurry+E	SE **1**
2	Slurry+T	ST **2**	2	Slurry+E	SE **2**
3	Slurry+T	ST **3**	3	Slurry+E	SE **3**
1	Soil+Slurry+T	SST **1**	1	Soil+Slurry+E	SSE **1**
2	Soil+Slurry+T	SST **2**	2	Soil+Slurry+E	SSE **2**
3	Soil+Slurry+T	SST **3**	3	Soil+Slurry+E	SSE **3**
1	Straw+Slurry+T 25°C	SST25 **1**	1	Straw+Slurry+E 25°C	SSE25 **1**
2	Straw+Slurry+T 25°C	SST25 **2**	2	Straw+Slurry+E 25°C	SSE25 **2**
3	Straw+Slurry+T 25°C	SST25 **3**	3	Straw+Slurry+E 25°C	SSE25 **3**
1	Woodchip+Slurry+T 25°C	WST25 **1**	1	Woodchip+Slurry+E 25°C	WSE25 **1**
2	Woodchip+Slurry+T 25°C	WST25 **2**	2	Woodchip+Slurry+E 25°C	WSE25 **2**
3	Woodchip+Slurry+T 25°C	WST25 **3**	3	Woodchip+Slurry+E 25°C	WSE25 **3**
1	Straw+Slurry+T 60°C	SST60 **1**	1	Straw+Slurry+E 60°C	SSE60 **1**
2	Straw+Slurry+T 60°C	SST60 **2**	2	Straw+Slurry+E 60°C	SSE60 **2**
3	Straw+Slurry+T 60°C	SST60 **3**	3	Straw+Slurry+E 60°C	SSE60 **3**
1	Woodchip+Slurry+T 60°C	WST60 **1**	1	Woodchip+Slurry+E 60°C	WSE60 **1**
2	Woodchip+Slurry+T 60°C	WST60 **2**	2	Woodchip+Slurry+E 60°C	WSE60 **2**
3	Woodchip+Slurry+T 60°C	WST60 **3**	3	Woodchip+Slurry+E 60°C	WSE60 **3**

Temperature ramps for 60° C compost treatments

Intervals	˚C	sem ± (n=6)
2 days	19	3.22
4 days	40	8.28
6 days	50	7.89
8 days	55	5.09
10 days	61	2.04
12 days	62	1.23
2 weeks	60	1.13
3 weeks	58	3.11
4 weeks	56	2.37
5 weeks	56	2.45
6 weeks	53	4.05



The table above shows the mean temperature gradient of 6 cattle manure composts: 3 woodchip-manure from ADAS and 3 straw-manure; 1 from ADAS and 2 from IGER.

Randomised Bench-top blocks

Estradiol treatments in pink; testosterone treatments in blue

ST1	SST25 1
WSE25 1	SE1
WST25 1	SSE25 1
SST1	SSE1

ST2	SSE25 2
SSE2	WSE25 2
WST25 2	SST2
SE2	SST25 2

SE3	WSE25 3
SST25 3	ST3
SSE25 3	SST3
WST25 3	SSE3

Randomised 60° C incubator blocks

SSE60 1
WST60 1
WSE60 1
SST60 1

SST60 2
SSE60 2
WSE60 2
WST60 2

WSE60 3
SST60 3
WST60 3
SSE60 3

Table 1

Present all background data for parent materials Woodchip, Straw, Manure and Soil.

Table 2

% Recovery of spiked [^{14}C] hormones via water extracts at the start and end of treatment processes

Table 3

Rate constants

Figure 1

Mean temperature ramps from an amalgam of cattle composts at ADAS and IGER trails to demonstrate how method for lab active composting was developed. See previous page.

Figure 2

^{14}C evolution in Testosterone inoculated treatments

Figure 3

^{14}C evolution in 17β-estradiol inoculated treatments

A5.4 Manure: Bedding ratio

Data on cattle excrement/day from DEFRA, RB-209, section 2 was applied to a space/head housing regime, based on DEFRA's regulatory guidelines, to calculate a standardised, 'livestock-weight dependant' manure: bedding ratio over 16 weeks housing. (DEFRA; rb209 Section 2)

Woodchip at 50 % mc (wet weight)

Cattle weight	Housing (wks)	Total woodchip required/head (kg)	Total undiluted excreta/head (kg)	g of bedding / g's of excreta
400 kg	16	792	2882	**3.64**
500 kg	16	1318	3559	2.70
550 kg	16	1318	5646	4.28

Woodchip at 40 % mc (wet weight)

Livestock Type	Housing (wks)	Total woodchip required/head (kg)	Total undiluted excreta/head (kg)	g's of excreta / g of bedding
400 kg	16	754	2882	**3.82**
500 kg	16	1257	3559	2.83
550 kg	16	1257	5646	4.49

Woodchip at 30 % mc (wet weight)

Livestock Type	Housing (wks)	Total woodchip required/head (kg)	Total undiluted excreta/head (kg)	g's of excreta / g of bedding
400 kg	16	722	2882	**3.99**
500 kg	16	1204	3559	2.96
550 kg	16	1204	5646	4.69

Woodchip at 20 % mc (wet weight)

Livestock Type	Housing (wks)	Total woodchip required/head (kg)	Total undiluted excreta/head (kg)	g's of excreta / g of bedding
400 kg	16	697	2882	**4.13**
500 kg	16	1161	3559	3.07
550 kg	16	1161	5646	4.86

Straw at 8-11 % mc (wet weight)

Livestock Type	Housing (wks)	Total straw required/head (kg)	Total undiluted excreta/head (kg)	g's of excreta / g of bedding
400 kg	16	281	2882	**10.3**
500 kg	16	469	3559	7.59
550 kg	16	469	5646	12.0

The table below shows the corresponding % of NPK within the waste

Stock type / head	**% N content**	**% P (P_2O_5)**	**% K (K_2O)**
Dairy cow (550 kg)	0.5	0.2	0.5
Beef stock (500kg)	0.52	0.2	0.52
Beef stock (400kg)	0.5	0.2	0.52

A5.5 Calculating hormone quantities, (T and E)

Volume of a cylinder $V=\pi r^2 h$

Assuming the jar has a diameter of 5 cm (r = 2.5 cm) it would be filled up to 5 cm, therefore:

$3.142 \times 2.5^2 \times 5 = 98.17\ cm^3$

The best way to work out bedding-manure ratio is to test what weight of (unpacked) straw would fill $98.17 cm^3$ and add weight of manure according to the above ratio (1:10.3)

Example: if $98.17\ cm^3$ of straw weights 8g then add 82.4 g of manure etc.

Roughly speaking, the straw volume will be absorbed into the manure, whereas the denser, solid woodchip will keep its volume in the jam jar after the manure is added, so the (1:4) ratio of woodchip-manure will result in roughly the same total volume as the (1:10) manure-straw treatments.

Calculate the volume-mass figure for the manure (1 cm^3= # grams) then estimate the volume of composts based on MC of woodchip beddings using the tables above.

A5.6 Statistical Analysis

T and E results analysed independently but under the same statistical treatments.
The central pillar of the analysis would be an ANOVA or GLM for each hormone, comparing all treatments against each other. Of particular interest would be:

- Active WC vs. Active Straw and to lesser extent – Static WC vs. Static Straw
- Static Straw vs. Slurry only vs. Slurry + Soil
- Static Woodchip vs. Slurry only vs. Slurry + Soil

Furthermore a combined analyses of results between;

- Active – Static (both woodchip and straw)
- Woodchip – Straw (both active and static)

A5.7 Feedstock background and Analysis

pH

The table below shows how the manure neutralises the acidic wood so that it has the same pH as straw-manure even before composting:

ADAS pH before and after composting

Treatment	Before bedding	After bedding, before composting	After composting
Woodchip 34 %	3.4	8.3	8.1
Woodchip 53 %	4.2	8.3	8.5
Woodchip 55 %	4.0	8.1	8.6
Straw	7.7	8.2	8.5

All woodchip treatments at IGER and Glynllifon showed the same pH pattern.

Electrical Conductivity (EC)

Electrical conductivity (EC) is a means of measuring total soluble salt content and is used to assess the potential risk of salt injury to plants. EC readings of up to 8.5 mS/cm were found in the composts, but it must be remembered these concentrations will be greatly reduced when dispersed on to land. The values were similar to those of conventional manure-based composts.

HCS - Slurry

Two slurries were collected from neighbouring farms near Chester, Cheshire. (Slurry 1) OS: SJ 349 722 and (Slurry 2) OS: SJ 350 724. No lime or detergents are used on either premises.

Slurry 1 – generated over 2 weeks by 120 beef bullocks and heifers of mixed breeds, all aged 1 to 2 years and fed first cut grass silage. The stock was transient over the 2 week period as animals were bought and sold, but the gender split remained approximately 65 % male / 35 % female, of which none were pregnant, although the number of resident heifers in oestrous was unknown.

Slurry 2 – collected from a 14 year old cow, not pregnant or in estrous, and an 18 month old entire bullock, both fed organic hay.

Soil

Sandy clay loam textured Eutric Cambisol collected from the surface Ah horizon (5–20 cm) of a lowland (15 m altitude) freely draining, heavily sheep-grazed grassland which receives regular fertilisation (120 kg N, 60 kg K and 10 kg P yr_1) and occasional manure addition.

Chemical and Physical characteristics of the soil used in the study:

	Eutric Cambisol
$EC_{1:1}$ ($\mu S\ cm^{-1}$)	80 ± 4
pH ($_{1:1}$, H_2O)	6.06 ± 0.07
$CaCO_3$ ($g\ kg^{-1}$)	0.11 ± 0.02
Water holding capacity ($g\ kg^{-1}$)	520 ± 20
Dry bulk density ($g\ cm^{-3}$)	0.93 ± 0.03
Moisture content ($g\ kg^{-1}$)	160 ± 10
Organic C ($g\ kg^{-1}$)	21 ± 0.1
Total N ($g\ kg^{-1}$)	0.16 ± 0.01
C-to-N ratio	13.3 ± 0.6
Soil solution NO_3^- ($mg\ N\ l^{-1}$)	13.7 ± 1.3
Soil solution NH_4^+ ($mg\ N\ l^{-1}$)	1.4 ± 0.1
Exchangeable cations	
Na ($mg\ kg^{-1}$)	29 ± 3
K ($mg\ kg^{-1}$)	116 ± 18
Ca ($mg\ kg^{-1}$)	1595 ± 217
Mg ($mg\ kg^{-1}$)	89 ± 19
Al ($mg\ kg^{-1}$)	22 ± 2
Extractable P ($mg\ kg^{-1}$)	9.9 ± 0.3
Soil respiration ($g\ CO_2\ m^{-2}\ h^{-1}$)	0.60 ± 0.02

All values represent means ± SEM ($n = 3$).
ND indicates not determined.

Method for Slurry, (Woodchip and Straw) Analysis

Before starting hormone exp. take 3x2 = 6 (A6 sized bags) reps of each material, freeze them – this means respiration analysis of slurry won't be possible. But other than that, do all the same analyses on slurry and beddings.

1. EC and pH
2. Water Holding Capacity, DM and MC
3. DOC and TSN → C:N ratio
4. NO_3^- and NH_4^+
5. Available P
6. K, Na, Ca (Mg and Al)

Measuring experimental environment factors

If possible use a Thermochron to record °C every half hour on bench-top – take mean recording for duration ±sem. alternatively, measure temp with thermometer that has a max and min facility and record humidity levels throughout.

APPENDIX VI

Table A6.1: Price sensitivity analysis of **chipping wood on-farm** for bedding **480 sheep**

Price of Wood £ t^{-1}	Sheep area allowance m^2 hd^{-1}	Woodchip volume applied m^3 hd^{-1}	Woodchip mass applied kg hd^{-1}	Cost of Woodchip applied £ hd^{-1}	Cost of N lost (1.36 kg hd^{-1}) at £0.30 kg^{-1}	Chipping Fuel & Labour £ hd^{-1}	BUY Dep. + Maint. £ hd^{-1}	HIRE Cost of hire £ hd^{-1}	Storage and handling £ hd^{-1}	BUY Chipper £ hd^{-1} in Year 1	HIRE Chipper £ hd^{-1} in Year 1	BUY Chipper £ hd^{-1} in Year 2	HIRE Chipper £ hd^{-1} in Year 2	BUY Chipper £ hd^{-1} yr^{-1} over 5 yrs.	HIRE Chipper £ hd^{-1} yr^{-1} over 5 yrs.
5	1.00	0.45	140	0.70	0.53	0.42	2.01	0.21	0.14	3.80	1.99	2.89	1.10	3.07	1.28
5	1.33	0.60	186	0.93	0.53	0.55	2.02	0.21	0.19	4.22	2.41	3.01	1.22	3.25	1.46
5	1.50	0.68	209	1.05	0.53	0.62	2.03	0.21	0.21	4.44	2.62	3.07	1.28	3.35	1.55
5	2.00	0.90	279	1.40	0.53	0.83	2.04	0.21	0.28	5.08	3.25	3.26	1.47	3.62	1.82
5	2.50	1.13	349	1.74	0.53	1.04	2.06	0.21	0.35	5.72	3.87	3.44	1.65	3.90	2.09
15	1.00	0.45	140	2.09	0.53	0.42	2.01	0.21	0.14	5.20	3.39	3.17	1.38	3.57	1.78
15	1.33	0.60	186	2.78	0.53	0.55	2.02	0.21	0.19	6.08	4.26	3.38	1.59	3.92	2.13
15	1.50	0.68	209	3.14	0.53	0.62	2.03	0.21	0.21	6.54	4.72	3.49	1.70	4.10	2.31
15	2.00	0.90	279	4.19	0.53	0.83	2.04	0.21	0.28	7.87	6.04	3.81	2.02	4.63	2.83
15	2.50	1.13	349	5.23	0.53	1.04	2.06	0.21	0.35	9.21	7.36	4.14	2.35	5.15	3.35
30	1.00	0.45	140	4.2	0.53	0.42	2.01	0.21	0.14	7.29	5.48	3.59	1.80	4.33	2.54
30	1.33	0.60	186	5.6	0.53	0.55	2.02	0.21	0.19	8.86	7.05	3.94	2.15	4.92	3.13
30	1.50	0.68	209	6.3	0.53	0.62	2.03	0.21	0.21	9.68	7.86	4.12	2.33	5.23	3.44
30	2.00	0.90	279	8.4	0.53	0.83	2.04	0.21	0.28	12.06	10.23	4.65	2.86	6.13	4.33
30	2.50	1.13	349	10.5	0.53	1.04	2.06	0.21	0.35	14.45	12.60	5.18	3.39	7.04	5.23

Table A6.2: Price sensitivity analysis of **chipping wood on-farm** for bedding **72 cattle**

Price of Wood £ t^{-1}	Cattle area allowance m^2 hd^{-1}	Woodchip volume applied m^3 hd^{-1}	Woodchip mass applied kg hd^{-1}	Cost of Woodchip applied £ hd^{-1}	Cost of N lost (8.6 kg hd^{-1}) at £0.30 kg^{-1}	Chipping Fuel & Labour £ hd^{-1}	BUY Dep. + Maint. £ hd^{-1}	HIRE Cost of hire £ hd^{-1}	Storage and handling £ hd^{-1}	BUY Chipper £ hd^{-1} in Year 1	HIRE Chipper £ hd^{-1} in Year 1	BUY Chipper £ hd^{-1} in Year 2	HIRE Chipper £ hd^{-1} in Year 2	BUY Chipper £ hd^{-1} yr^{-1} over 5 yrs.	HIRE Chipper £ hd^{-1} yr^{-1} over 5 yrs.
5	4.0	3.40	1055	5.27	2.58	3.14	13.46	1.39	1.05	25.51	13.44	18.61	6.71	19.99	8.05
5	4.5	3.83	1186	5.93	2.58	3.54	13.48	1.39	1.19	26.72	14.62	18.96	7.05	20.51	8.56
5	5.0	4.25	1318	6.59	2.58	3.93	13.51	1.39	1.32	27.93	15.81	19.30	7.39	21.03	9.07
5	5.5	4.68	1450	7.25	2.58	4.32	13.54	1.39	1.45	29.14	16.99	19.65	7.73	21.55	9.59
5	6.0	5.10	1582	7.91	2.58	4.71	13.56	1.39	1.58	30.35	18.17	20.00	8.08	22.07	10.10
15	4.0	3.40	1055	15.82	2.58	3.14	13.46	1.39	1.05	36.05	23.99	20.72	8.82	23.79	11.85
15	4.5	3.83	1186	17.80	2.58	3.54	13.48	1.39	1.19	38.58	26.49	21.33	9.42	24.78	12.84
15	5.0	4.25	1318	19.77	2.58	3.93	13.51	1.39	1.32	41.11	28.99	21.94	10.03	25.77	13.82
15	5.5	4.68	1450	21.75	2.58	4.32	13.54	1.39	1.45	43.64	31.49	22.55	10.63	26.77	14.81
15	6.0	5.10	1582	23.73	2.58	4.71	13.56	1.39	1.58	46.17	33.99	23.16	11.24	27.76	15.79
30	4.0	3.40	1055	31.64	2.58	3.14	13.46	1.39	1.05	51.87	39.80	23.88	11.98	29.48	17.54
30	4.5	3.83	1186	35.59	2.58	3.54	13.48	1.39	1.19	56.38	44.28	24.89	12.98	31.19	19.24
30	5.0	4.25	1318	39.55	2.58	3.93	13.51	1.39	1.32	60.88	48.76	25.90	13.98	32.89	20.94
30	5.5	4.68	1450	43.50	2.58	4.32	13.54	1.39	1.45	65.39	53.24	26.90	14.98	34.60	22.64
30	6.0	5.10	1582	47.46	2.58	4.71	13.56	1.39	1.58	69.89	57.72	27.91	15.99	36.31	24.33

Table A6.3: Price sensitivity analysis of **chipping wood on-farm** for bedding **2400 sheep**

Price of Wood £ t^{-1}	Sheep area allowance m^2 hd^{-1}	Woodchip volume applied m^3 hd^{-1}	Woodchip mass applied kg hd^{-1}	Cost of Woodchip applied £ hd^{-1}	Cost of N lost (1.36 kg hd^{-1}) at £0.30 kg^{-1}	Chipping Fuel & Labour £ hd^{-1}	BUY Dep. + Maint. £ hd^{-1}	HIRE Cost of hire £ hd^{-1}	Storage and handling £ hd^{-1}	BUY Chipper £ hd^{-1} in Year 1	HIRE Chipper £ hd^{-1} in Year 1	BUY Chipper £ hd^{-1} in Year 2	HIRE Chipper £ hd^{-1} in Year 2	BUY Chipper £ hd^{-1} yr^{-1} over 5 yrs.	HIRE Chipper £ hd^{-1} yr^{-1} over 5 yrs.
5	1.00	0.45	140	0.70	0.53	0.42	0.42	0.10	0.14	2.21	1.89	1.30	1.00	1.48	1.18
5	1.33	0.60	186	0.93	0.53	0.55	0.43	0.10	0.19	2.63	2.30	1.42	1.12	1.66	1.36
5	1.50	0.68	209	1.05	0.53	0.62	0.44	0.10	0.21	2.85	2.52	1.48	1.18	1.76	1.45
5	2.00	0.90	279	1.40	0.53	0.83	0.45	0.10	0.28	3.49	3.14	1.67	1.36	2.03	1.72
5	2.50	1.13	349	1.74	0.53	1.04	0.47	0.10	0.35	4.13	3.77	1.85	1.54	2.31	1.99
15	1.00	0.45	140	2.09	0.53	0.42	0.42	0.10	0.14	3.61	3.29	1.58	1.28	1.98	1.68
15	1.33	0.60	186	2.78	0.53	0.55	0.43	0.10	0.19	4.49	4.16	1.79	1.49	2.33	2.02
15	1.50	0.68	209	3.14	0.53	0.62	0.44	0.10	0.21	4.95	4.61	1.90	1.60	2.51	2.20
15	2.00	0.90	279	4.19	0.53	0.83	0.45	0.10	0.28	6.28	5.94	2.22	1.92	3.04	2.72
15	2.50	1.13	349	5.23	0.53	1.04	0.47	0.10	0.35	7.62	7.26	2.55	2.24	3.56	3.24
30	1.00	0.45	140	4.2	0.53	0.42	0.42	0.10	0.14	5.70	5.38	2.00	1.70	2.74	2.43
30	1.33	0.60	186	5.6	0.53	0.55	0.43	0.10	0.19	7.27	6.95	2.35	2.05	3.33	3.03
30	1.50	0.68	209	6.3	0.53	0.62	0.44	0.10	0.21	8.09	7.75	2.53	2.23	3.64	3.33
30	2.00	0.90	279	8.4	0.53	0.83	0.45	0.10	0.28	10.47	10.12	3.06	2.76	4.54	4.23
30	2.50	1.13	349	10.5	0.53	1.04	0.47	0.10	0.35	12.86	12.49	3.59	3.29	5.45	5.13

Table A6.4: Price sensitivity analysis of **chipping wood on-farm** for bedding **360 cattle**

Price of Wood £ t^{-1}	Cattle area allowance m^2 hd^{-1}	Woodchip volume applied m^3 hd^{-1}	Woodchip mass applied kg hd^{-1}	Cost of Woodchip applied £ hd^{-1}	Cost of N lost (8.6 kg hd^{-1}) at £0.30 kg^{-1}	Chipping Fuel & Labour £ hd^{-1}	Option 1 Dep. + Maint. £ hd^{-1}	Option 2 Cost of hire £ hd^{-1}	Storage and handling £ hd^{-1}	BUY Chipper £ hd^{-1} in Year 1	HIRE Chipper £ hd^{-1} in Year 1	BUY Chipper £ hd^{-1} in Year 2	HIRE Chipper £ hd^{-1} in Year 2	BUY Chipper £ hd^{-1} yr^{-1} over 5 yrs.	HIRE Chipper £ hd^{-1} yr^{-1} over 5 yrs.
5	4.00	3.40	1055	5.27	2.58	3.14	2.86	0.69	1.05	14.91	12.75	8.01	6.01	9.39	7.36
5	4.50	3.83	1186	5.93	2.58	3.54	2.88	0.69	1.19	16.12	13.93	8.36	6.35	9.91	7.87
5	5.00	4.25	1318	6.59	2.58	3.93	2.91	0.69	1.32	17.33	15.11	8.70	6.70	10.43	8.38
5	5.50	4.68	1450	7.25	2.58	4.32	2.94	0.69	1.45	18.54	16.30	9.05	7.04	10.95	8.89
5	6.00	5.10	1582	7.91	2.58	4.71	2.96	0.69	1.58	19.75	17.48	9.40	7.38	11.47	9.40
15	4.00	3.40	1055	15.8	2.58	3.14	2.86	0.69	1.05	25.45	23.29	10.12	8.12	13.19	11.16
15	4.50	3.83	1186	17.8	2.58	3.54	2.88	0.69	1.19	27.98	25.79	10.73	8.73	14.18	12.14
15	5.00	4.25	1318	19.8	2.58	3.93	2.91	0.69	1.32	30.51	28.30	11.34	9.33	15.17	13.13
15	5.50	4.68	1450	21.8	2.58	4.32	2.94	0.69	1.45	33.04	30.80	11.95	9.94	16.17	14.11
15	6.00	5.10	1582	23.7	2.58	4.71	2.96	0.69	1.58	35.57	33.30	12.56	10.55	17.16	15.10
30	4.00	3.40	1055	31.6	2.58	3.14	2.86	0.69	1.05	41.27	39.11	13.28	11.29	18.88	16.85
30	4.50	3.83	1186	35.6	2.58	3.54	2.88	0.69	1.19	45.78	43.59	14.29	12.29	20.59	18.55
30	5.00	4.25	1318	39.5	2.58	3.93	2.91	0.69	1.32	50.28	48.07	15.30	13.29	22.29	20.24
30	5.50	4.68	1450	43.5	2.58	4.32	2.94	0.69	1.45	54.79	52.55	16.30	14.29	24.00	21.94
30	6.00	5.10	1582	47.5	2.58	4.71	2.96	0.69	1.58	59.29	57.03	17.31	15.29	25.71	23.64

Table A6.5: Price sensitivity analysis of a group of 5 farmers with 480 sheep each, sharing the costs of buying or hiring a chipper

Price of Wood £ t^{-1}	Sheep area allowance m^2 hd^{-1}	Woodchip volume applied m^3 hd^{-1}	Woodchip mass applied kg hd^{-1}	Cost of Woodchip applied £ hd^{-1}	Cost of N lost (1.36 kg hd^{-1}) at £0.30 kg^{-1}	Chipping Fuel & Labour £ hd^{-1}	BUY Dep. + Maint. £ hd^{-1}	HIRE Chipper Hire £ hd^{-1}	Storage and handling £ hd^{-1}	BUY Chipper £ hd^{-1} in Year 1	HIRE Chipper £ hd^{-1} in Year 1	BUY Chipper £ hd^{-1} in Year 2	HIRE Chipper £ hd^{-1} in Year 2	BUY Chipper £ hd^{-1} yr^{-1} over 5 yrs.	HIRE Chipper £ hd^{-1} yr^{-1} over 5 yrs.
5	1.00	0.45	140	0.70	0.53	0.42	0.40	0.10	0.14	2.19	1.89	1.29	1.00	1.47	1.18
5	1.33	0.60	186	0.93	0.53	0.55	0.40	0.10	0.19	2.60	2.30	1.41	1.12	1.65	1.36
5	1.50	0.68	209	1.05	0.53	0.62	0.41	0.10	0.21	2.82	2.52	1.48	1.18	1.74	1.45
5	2.00	0.90	279	1.40	0.53	0.83	0.41	0.10	0.28	3.45	3.14	1.66	1.36	2.02	1.72
5	2.50	1.13	349	1.74	0.53	1.04	0.41	0.10	0.35	4.08	3.77	1.84	1.54	2.29	1.99
15	1.00	0.45	140	2.09	0.53	0.42	0.40	0.10	0.14	3.59	3.29	1.57	1.28	1.98	1.68
15	1.33	0.60	186	2.78	0.53	0.55	0.40	0.10	0.19	4.46	4.16	1.79	1.49	2.32	2.02
15	1.50	0.68	209	3.14	0.53	0.62	0.41	0.10	0.21	4.91	4.61	1.89	1.60	2.50	2.20
15	2.00	0.90	279	4.19	0.53	0.83	0.41	0.10	0.28	6.24	5.94	2.22	1.92	3.02	2.72
15	2.50	1.13	349	5.23	0.53	1.04	0.41	0.10	0.35	7.57	7.26	2.54	2.24	3.54	3.24
30	1.00	0.45	140	4.2	0.53	0.42	0.40	0.10	0.14	5.68	5.38	1.99	1.70	2.73	2.43
30	1.33	0.60	186	5.6	0.53	0.55	0.40	0.10	0.19	7.25	6.95	2.34	2.05	3.32	3.03
30	1.50	0.68	209	6.3	0.53	0.62	0.41	0.10	0.21	8.05	7.75	2.52	2.23	3.63	3.33
30	2.00	0.90	279	8.4	0.53	0.83	0.41	0.10	0.28	10.43	10.12	3.05	2.76	4.53	4.23
30	2.50	1.13	349	10.5	0.53	1.04	0.41	0.10	0.35	12.80	12.49	3.58	3.29	5.43	5.13

Table A6.6: Price sensitivity analysis of a group of 5 farmers with 72 cattle each, sharing the costs of buying or hiring a chipper

Price of Wood £ t^{-1}	Cattle area allowance m^2 hd^{-1}	Woodchip volume applied m^3 hd^{-1}	Woodchip mass applied kg hd^{-1}	Cost of Woodchip applied £ hd^{-1}	Cost of N lost (8.6 kg hd^{-1}) at £0.30 kg^{-1}	Chipping Fuel & Labour £ hd^{-1}	BUY Dep. + Maint. £ hd^{-1}	HIRE Chipper Hire £ hd^{-1}	Storage and handling £ hd^{-1}	BUY Chipper £ hd^{-1} in Year 1	HIRE Chipper £ hd^{-1} in Year 1	BUY Chipper £ hd^{-1} in Year 2	HIRE Chipper £ hd^{-1} in Year 2	BUY Chipper £ hd^{-1} yr^{-1} over 5 yrs.	HIRE Chipper £ hd^{-1} yr^{-1} over 5 yrs.
5	4.00	3.40	1055	5.27	2.58	3.14	2.69	0.69	1.05	14.74	12.75	7.98	6.01	9.33	7.36
5	4.50	3.83	1186	5.93	2.58	3.54	2.70	0.69	1.19	15.93	13.93	8.32	6.35	9.84	7.87
5	5.00	4.25	1318	6.59	2.58	3.93	2.70	0.69	1.32	17.12	15.11	8.66	6.70	10.35	8.38
5	5.50	4.68	1450	7.25	2.58	4.32	2.71	0.69	1.45	18.31	16.30	9.01	7.04	10.87	8.89
5	6.00	5.10	1582	7.91	2.58	4.71	2.71	0.69	1.58	19.50	17.48	9.35	7.38	11.38	9.40
15	4.00	3.40	1055	15.82	2.58	3.14	2.69	0.69	1.05	25.29	23.29	10.09	8.12	13.13	11.16
15	4.50	3.83	1186	17.80	2.58	3.54	2.70	0.69	1.19	27.80	25.79	10.69	8.73	14.11	12.14
15	5.00	4.25	1318	19.77	2.58	3.93	2.70	0.69	1.32	30.30	28.30	11.30	9.33	15.10	13.13
15	5.50	4.68	1450	21.75	2.58	4.32	2.71	0.69	1.45	32.81	30.80	11.91	9.94	16.09	14.11
15	6.00	5.10	1582	23.73	2.58	4.71	2.71	0.69	1.58	35.32	33.30	12.51	10.55	17.07	15.10
30	4.00	3.40	1055	31.6	2.58	3.14	2.69	0.69	1.05	41.11	39.11	13.25	11.29	18.82	16.85
30	4.50	3.83	1186	35.6	2.58	3.54	2.70	0.69	1.19	45.59	43.59	14.25	12.29	20.52	18.55
30	5.00	4.25	1318	39.5	2.58	3.93	2.70	0.69	1.32	50.08	48.07	15.25	13.29	22.22	20.24
30	5.50	4.68	1450	43.5	2.58	4.32	2.71	0.69	1.45	54.56	52.55	16.26	14.29	23.92	21.94
30	6.00	5.10	1582	47.5	2.58	4.71	2.71	0.69	1.58	59.05	57.03	17.26	15.29	25.62	23.64

Table A6.7: Price sensitivity analysis of buying **pre-chipped wood** for bedding **Sheep**

Price of Woodchip £ t^{-1}	Sheep area allowance m^2 hd^{-1}	Woodchip volume applied m^3 hd^{-1}	Woodchip mass applied kg hd^{-1}	Cost of Woodchip applied £ hd^{-1}	Cost of N lost (1.36 kg hd^{-1}) at £0.30 kg^{-1}	Storage and handling £ hd^{-1}	Woodchip £ hd^{-1} in Year 1	Woodchip £ hd^{-1} in Year 2	Woodchip £ hd^{-1} yr^{-1} over 5 yrs.
60	1.00	0.45	140	8.37	0.53	0.14	9.05	2.35	3.69
60	1.33	0.60	186	11.14	0.53	0.19	11.86	2.95	4.73
60	1.50	0.68	209	12.56	0.53	0.21	13.30	3.25	5.26
60	2.00	0.90	279	16.75	0.53	0.28	17.56	4.16	6.84
60	2.50	1.13	349	20.94	0.53	0.35	21.82	5.07	8.42
80	1.00	0.45	140	11.17	0.53	0.14	11.84	2.91	4.69
80	1.33	0.60	186	14.85	0.53	0.19	15.57	3.69	6.06
80	1.50	0.68	209	16.75	0.53	0.21	17.49	4.09	6.77
80	2.00	0.90	279	22.33	0.53	0.28	23.14	5.28	8.85
80	2.50	1.13	349	27.92	0.53	0.35	28.80	6.47	10.93

Table A6.8: Price sensitivity analysis of buying **pre-chipped wood** for bedding **Cattle**

Price of Woodchip £ t^{-1}	Cattle area allowance m^2 hd^{-1}	Woodchip volume applied m^3 hd^{-1}	Woodchip mass applied kg hd^{-1}	Cost of Woodchip applied £ hd^{-1}	Cost of N lost (8.6 kg hd^{-1}) at £0.30 kg^{-1}	Storage and handling £ hd^{-1}	Woodchip £ hd^{-1} in Year 1	Woodchip £ hd^{-1} in Year 2	Woodchip £ hd^{-1} yr^{-1} over 5 yrs.
60	4.0	3.40	1055	63.28	2.58	1.05	66.91	16.29	26.41
60	4.5	3.83	1186	71.18	2.58	1.19	74.95	18.00	29.39
60	5.0	4.25	1318	79.09	2.58	1.32	82.99	19.72	32.37
60	5.5	4.68	1450	87.00	2.58	1.45	91.03	21.43	35.35
60	6.0	5.10	1582	94.91	2.58	1.58	99.08	23.15	38.33
80	4.0	3.40	1055	84.37	2.58	1.05	88.00	20.51	34.01
80	4.5	3.83	1186	94.91	2.58	1.19	98.68	22.75	37.94
80	5.0	4.25	1318	105.46	2.58	1.32	109.36	24.99	41.86
80	5.5	4.68	1450	116.00	2.58	1.45	120.04	27.23	45.79
80	6.0	5.10	1582	126.55	2.58	1.58	130.71	29.47	49.72

Table A6.9: Price sensitivity analysis of buying **straw** for bedding **Sheep**

Price of Straw £ t^{-1}	Sheep area allowance m^2 hd^{-1}	Straw volume applied m^3 hd^{-1}	Straw mass applied kg hd^{-1}	Cost of Straw applied £ hd^{-1}	Cost of N lost (1.78 kg hd^{-1}) at £0.30 kg^{-1}	Storage and handling £ hd^{-1}	Annual straw bedding £ hd^{-1}
50	1.00	0.45	68	3.38	0.41	0.07	3.85
50	1.33	0.60	90	4.49	0.41	0.09	4.99
50	1.50	0.68	101	5.06	0.41	0.10	5.57
50	2.00	0.90	135	6.75	0.41	0.14	7.29
50	2.50	1.13	169	8.44	0.41	0.17	9.01
60	1.00	0.45	68	4.05	0.41	0.07	4.53
60	1.33	0.60	90	5.39	0.41	0.09	5.88
60	1.50	0.68	101	6.08	0.41	0.10	6.58
60	2.00	0.90	135	8.10	0.41	0.14	8.64
60	2.50	1.13	169	10.13	0.41	0.17	10.70
70	1.00	0.45	68	4.73	0.41	0.07	5.20
70	1.33	0.60	90	6.28	0.41	0.09	6.78
70	1.50	0.68	101	7.09	0.41	0.10	7.60
70	2.00	0.90	135	9.45	0.41	0.14	9.99
70	2.50	1.13	169	11.81	0.41	0.17	12.39
80	1.00	0.45	68	5.40	0.41	0.07	5.88
80	1.33	0.60	90	7.18	0.41	0.09	7.68
80	1.50	0.68	101	8.10	0.41	0.10	8.61
80	2.00	0.90	135	10.80	0.41	0.14	11.34
80	2.50	1.13	169	13.50	0.41	0.17	14.08

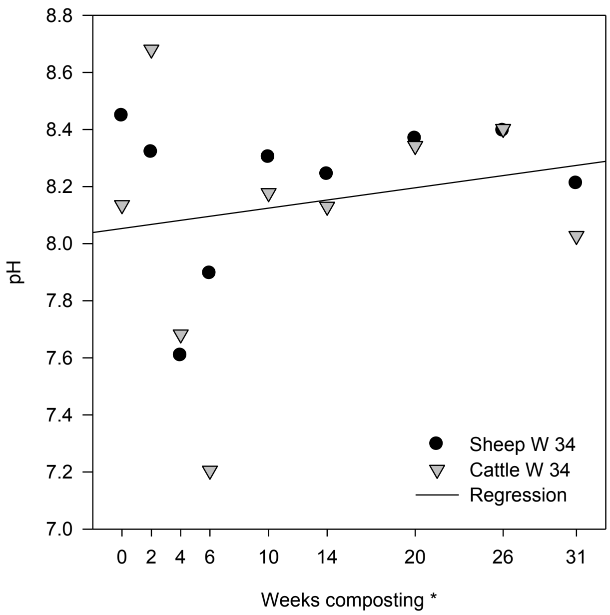
Table A6.10: Price sensitivity analysis of buying **straw** for bedding **cattle**

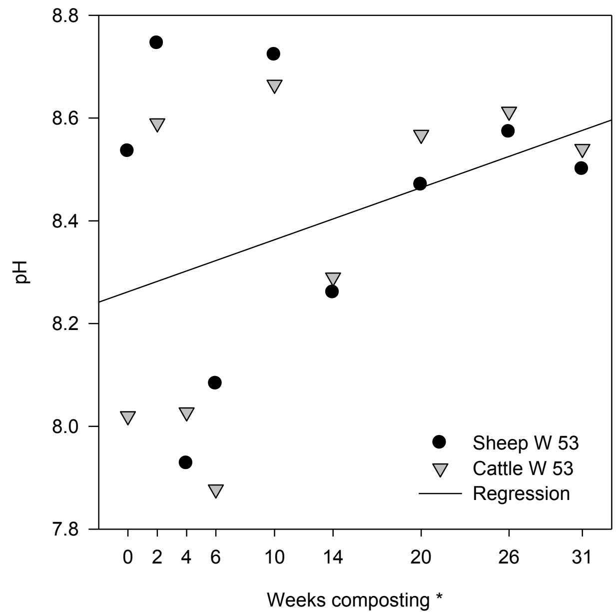
Price of Straw £ t^{-1}	Cattle area allowance m^2 hd^{-1}	Straw volume applied m^3 hd^{-1}	Straw mass applied kg hd^{-1}	Cost of Straw applied £ hd^{-1}	Cost of N lost (11.7 kg hd^{-1}) at £0.30 kg^{-1}	Storage and handling £ hd^{-1}	Annual straw bedding £ hd^{-1}
50	4.0	3.40	510	25.50	3.50	0.51	29.51
50	4.5	3.83	574	28.69	3.50	0.57	32.76
50	5.0	4.25	638	31.88	3.50	0.64	36.01
50	5.5	4.68	701	35.06	3.50	0.70	39.26
50	6.0	5.10	765	38.25	3.50	0.77	42.51
60	4.0	3.40	510	30.60	3.50	0.51	34.61
60	4.5	3.83	574	34.43	3.50	0.57	38.49
60	5.0	4.25	638	38.25	3.50	0.64	42.38
60	5.5	4.68	701	42.08	3.50	0.70	46.27
60	6.0	5.10	765	45.90	3.50	0.77	50.16
70	4.0	3.40	510	35.70	3.50	0.51	39.71
70	4.5	3.83	574	40.16	3.50	0.57	44.23
70	5.0	4.25	638	44.63	3.50	0.64	48.76
70	5.5	4.68	701	49.09	3.50	0.70	53.28
70	6.0	5.10	765	53.55	3.50	0.77	57.81
80	4.0	3.40	510	40.80	3.50	0.51	44.81
80	4.5	3.83	574	45.90	3.50	0.57	49.97
80	5.0	4.25	638	51.00	3.50	0.64	55.13
80	5.5	4.68	701	56.10	3.50	0.70	60.30
80	6.0	5.10	765	61.20	3.50	0.77	65.46

APPENDIX VII

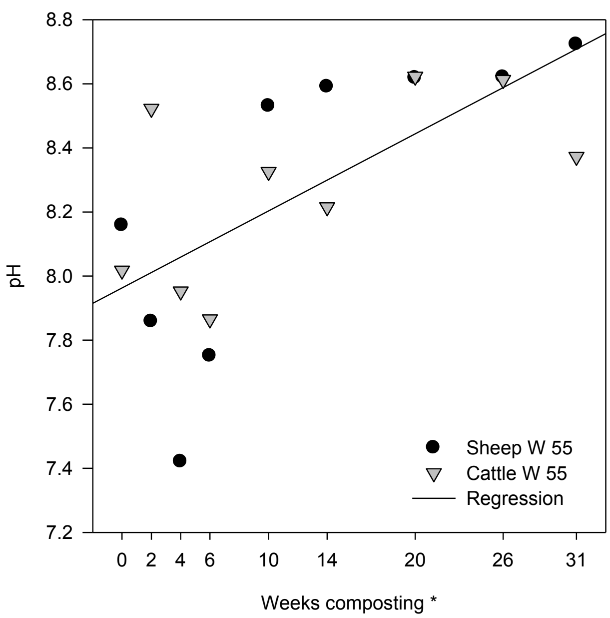
APENDIX – VII – Linear regression analysis of bedding types at ADAS

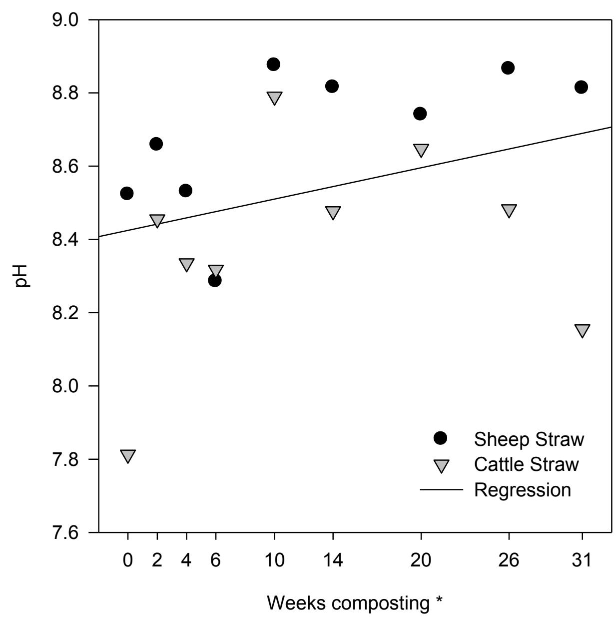
A7.1 pH



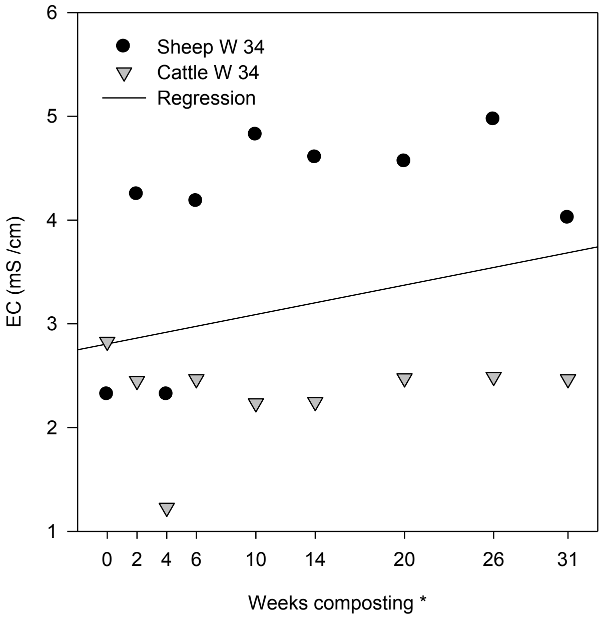


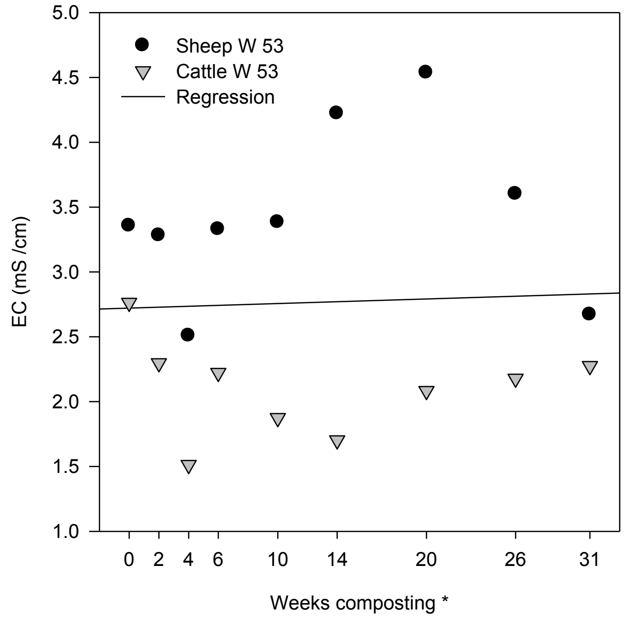
Treatment	Line equation	R^2	p. value
W34	y = 0.0071x + 8.0535	$R^2 = 0.0564$	.539
W53	y = 0.0101x + 8.2619	$R^2 = 0.1641$	.280
W55	y = 0.024x + 7.9631	$R^2 = 0.5869$	**.016**
Straw	y = 0.0086x + 8.4245	$R^2 = 0.2038$	.223



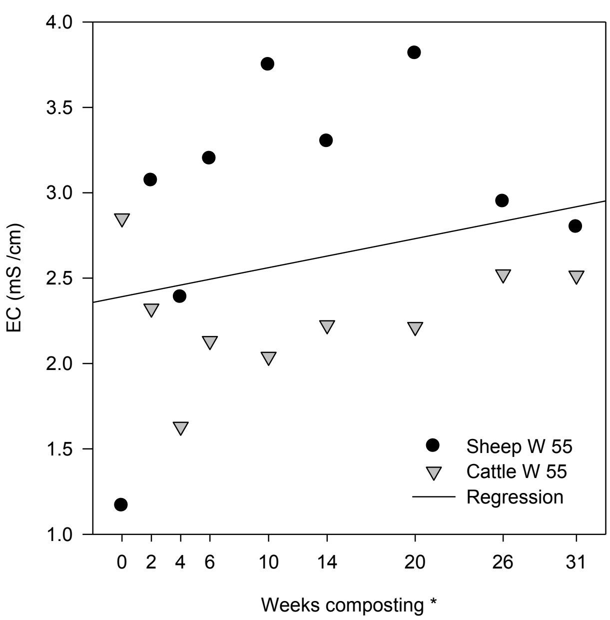


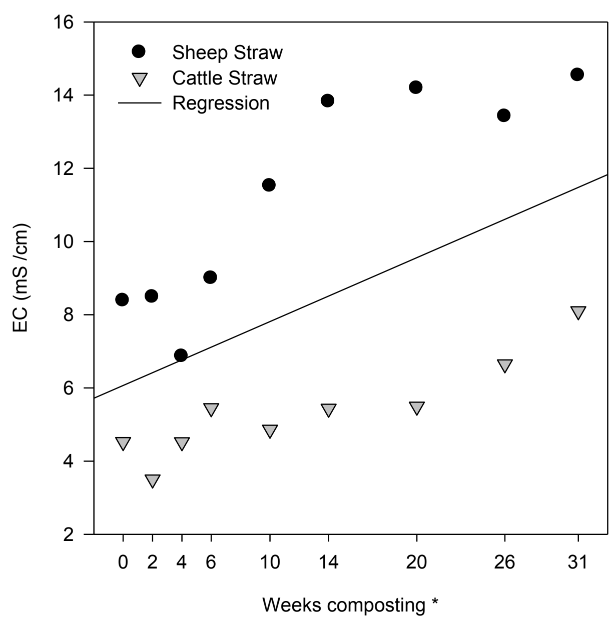
A7.2 EC



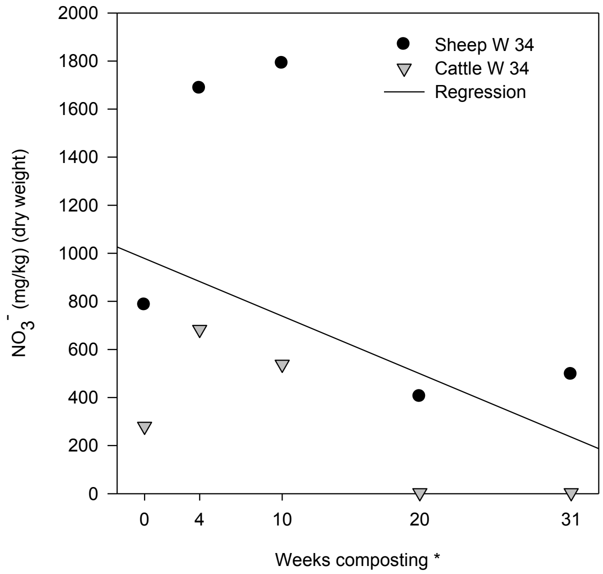


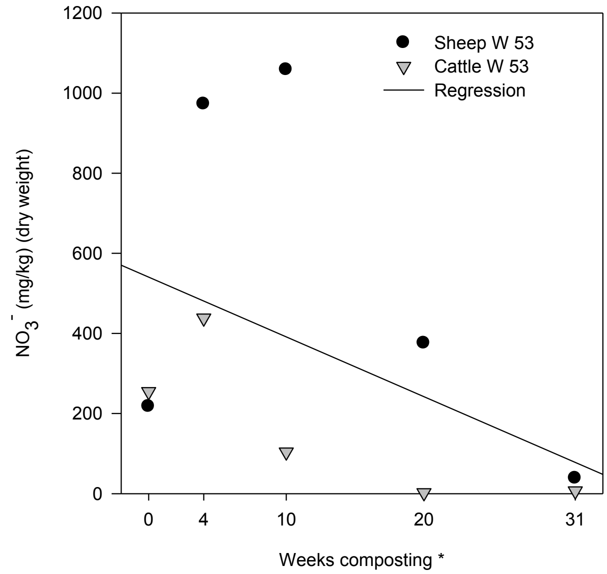
Treatment	Line equation	R^2	p. value
W34	y = 0.0283x + 2.8067	$R^2 = 0.2598$	.161
W53	y = 0.0035x + 2.7218	$R^2 = 0.0107$	.791
W55	y = 0.017x + 2.3913	$R^2 = 0.2744$	.148
Straw	y = -0.0353x + 7.9872	$R^2 = 0.013$	**.000**



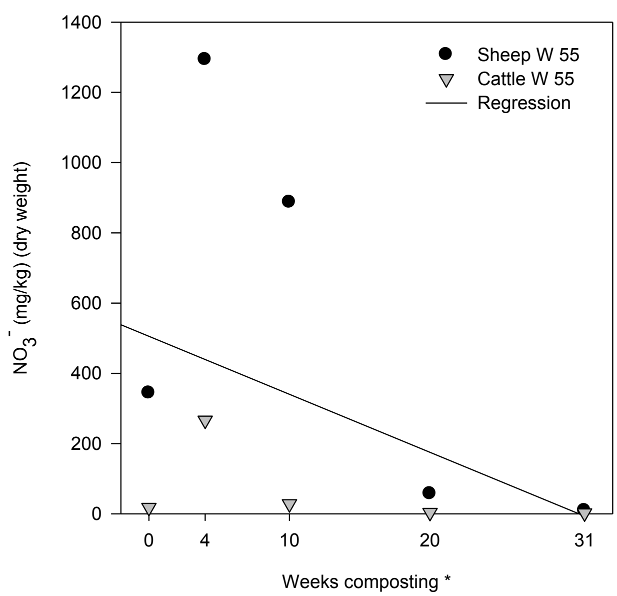


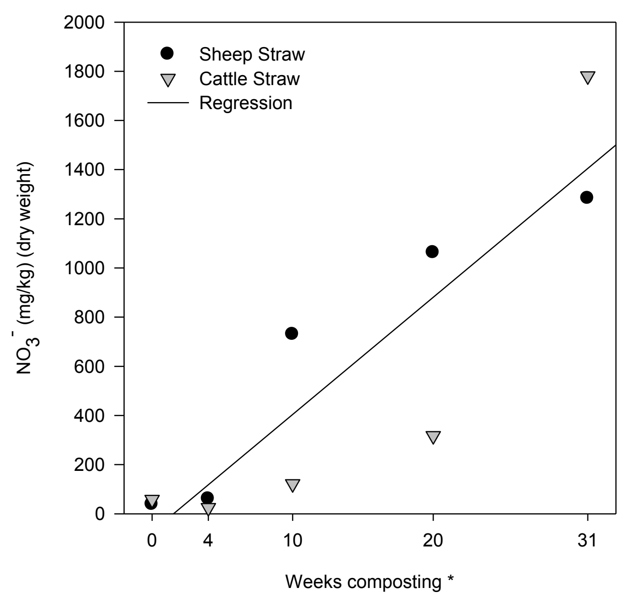
A7.3 Nitrate



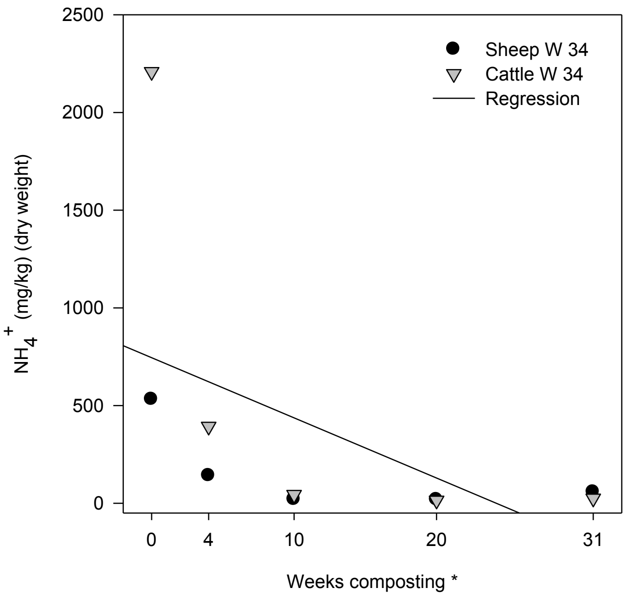


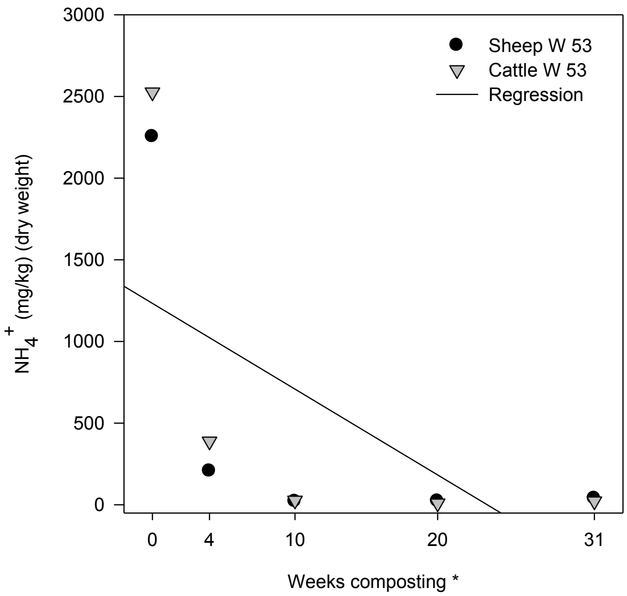
Treatment	Line equation	R^2	p. value
W34	y = -23.987x + 978.54	R^2 = 0.3943	.257
W53	y = -14.924x + 540.6	R^2 = 0.4319	.228
W55	y = -16.501x + 505.16	R^2 = 0.4018	.251
Straw	y = 47.655x - 72.246	R^2 = 0.9514	**.005**



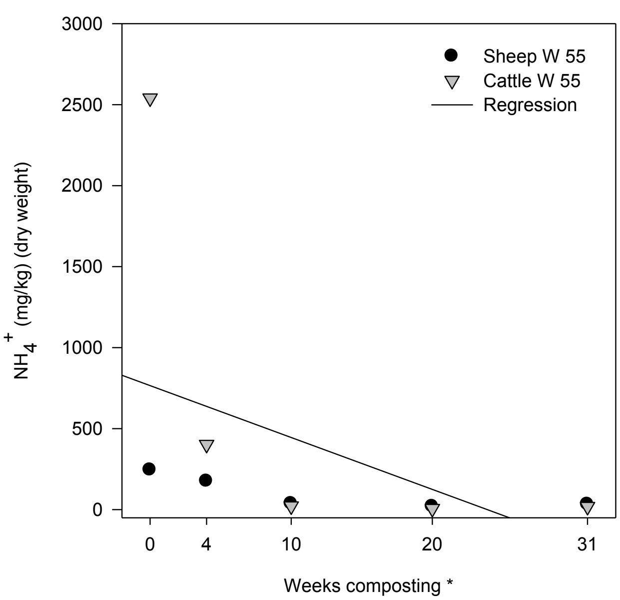


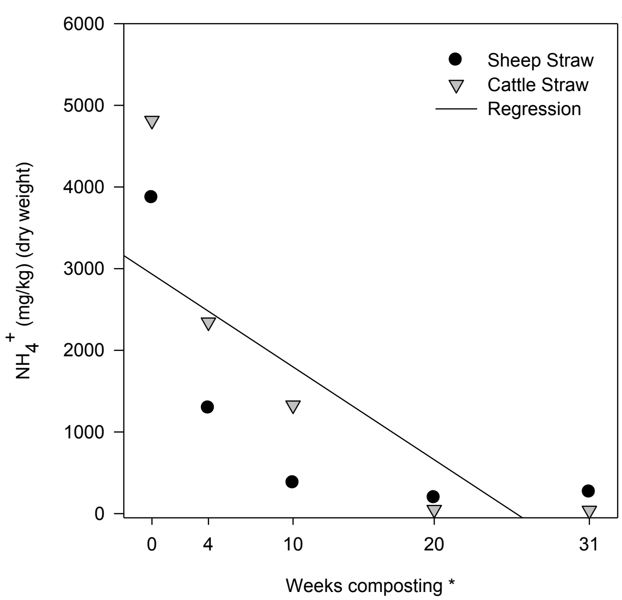
A7.4 Ammonium



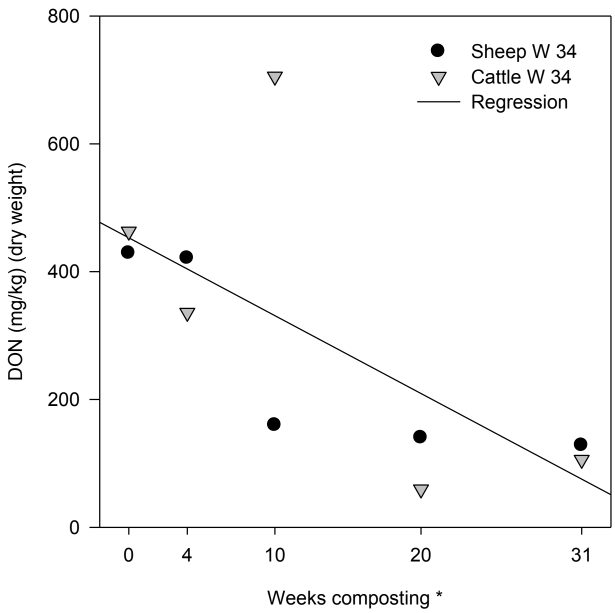


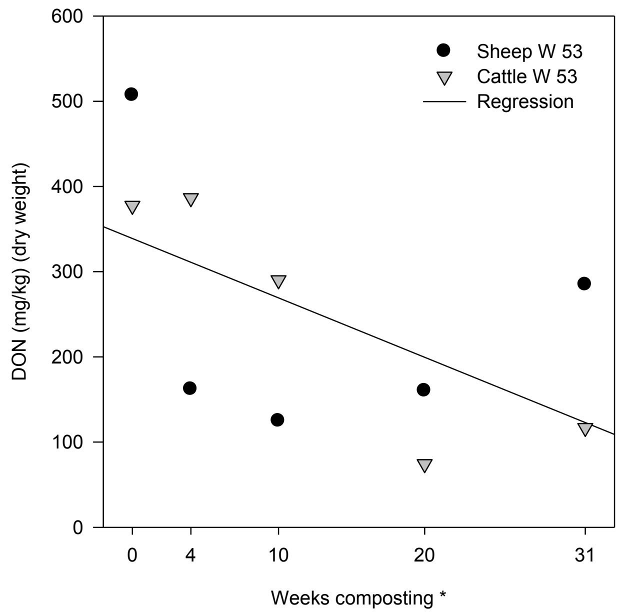
Treatment	Line equation	R^2	p. value
W34	y = -30.773x + 744.78	$R^2 = 0.4418$	.221
W53	y = -52.462x + 1232.9	$R^2 = 0.4063$	.247
W55	y = -32.003x + 765.33	$R^2 = 0.4588$	.209
Straw	y = -113.57x + 2932.1	$R^2 = 0.6629$	.093



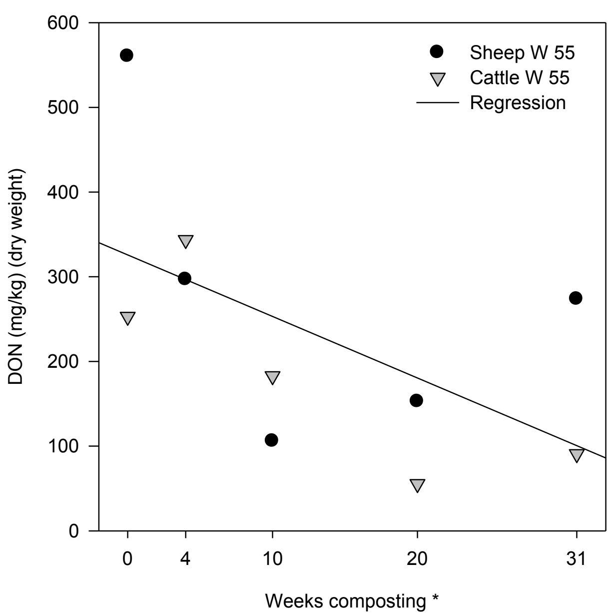


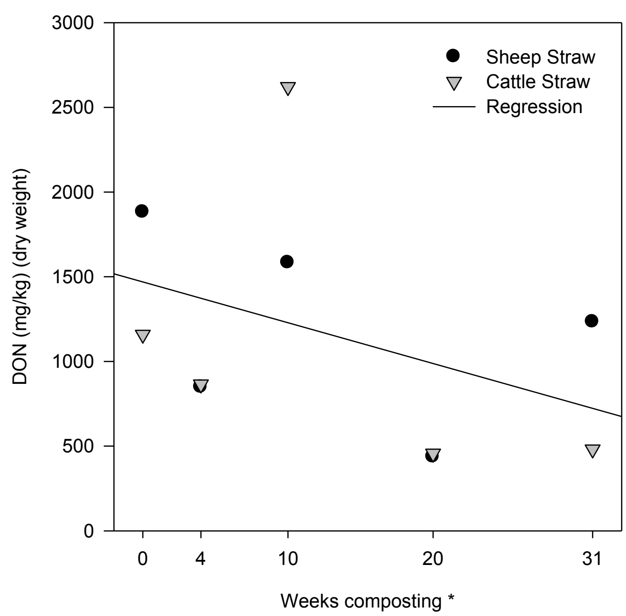
A7.5 Dissolved Organic Nitrogen (DON)



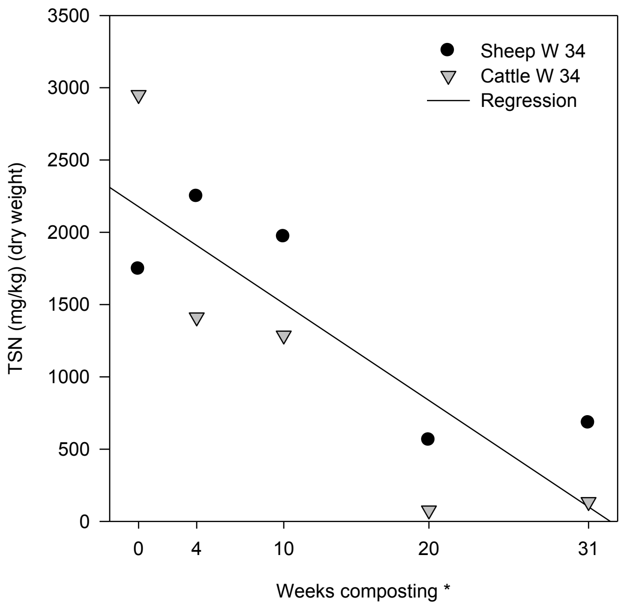


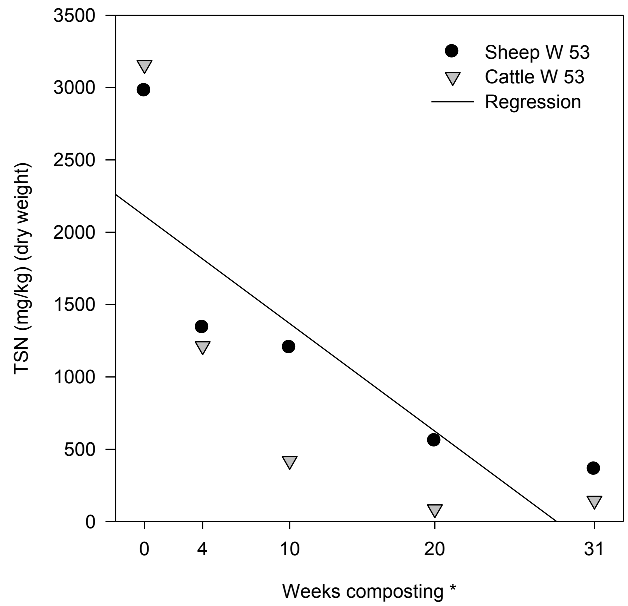
Treatment	Line equation	R^2	p. value
W34	y = -12.174x + 452.88	$R^2 = 0.7909$	**.043**
W53	y = -6.9681x + 338.88	$R^2 = 0.5168$	.171
W55	y = -7.2635x + 325.76	$R^2 = 0.5151$	.172
Straw	y = -24.082x + 1469.3	$R^2 = 0.2145$	.432



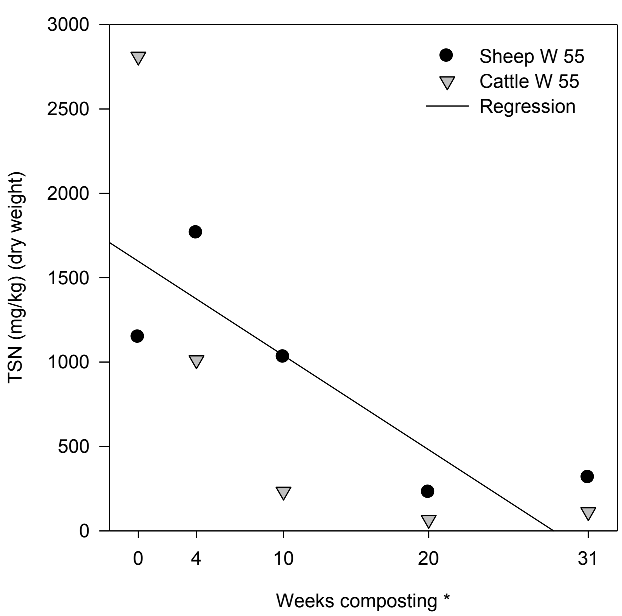


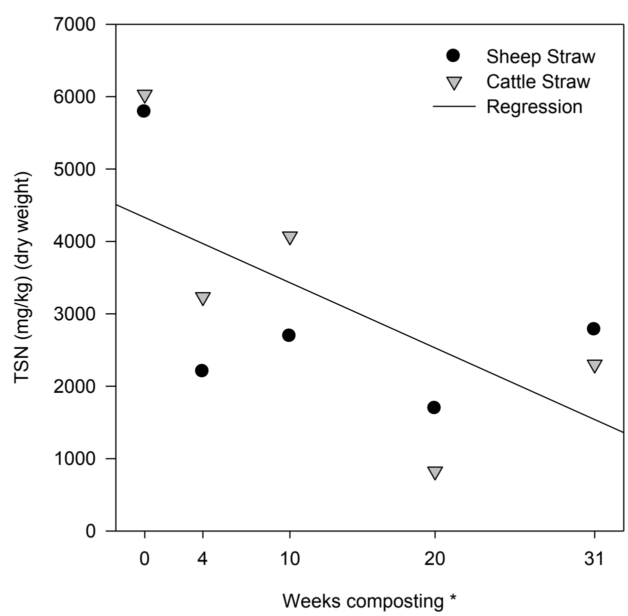
A7.6 Total Soluble Nitrogen (TSN)



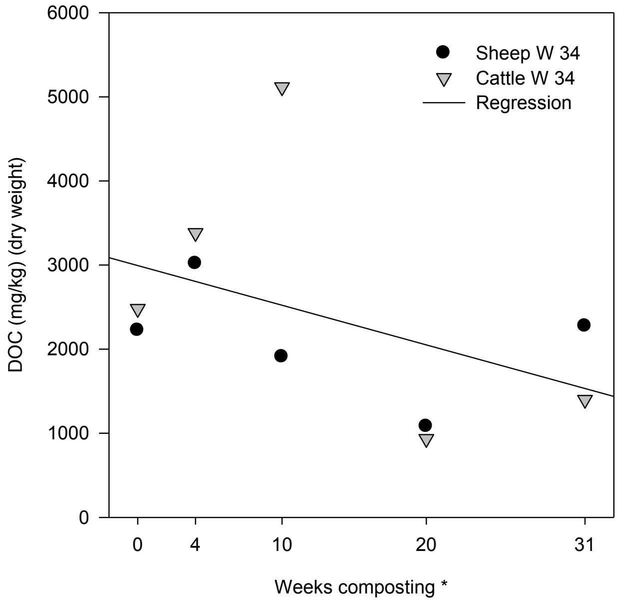


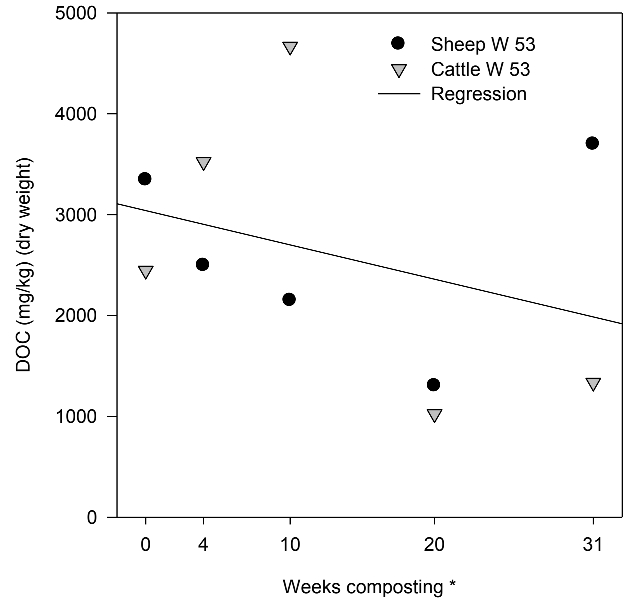
Treatment	Line equation	R^2	p. value
W34	y = -66.933x + 2176.2	$R^2 = 0.8728$	**.020**
W53	y = -74.354x + 2112.4	$R^2 = 0.6596$	.095
W55	y = -55.767x + 1596.2	$R^2 = 0.7833$	**.046**
Straw	y = -89.998x + 4329.1	$R^2 = 0.4338$	.227



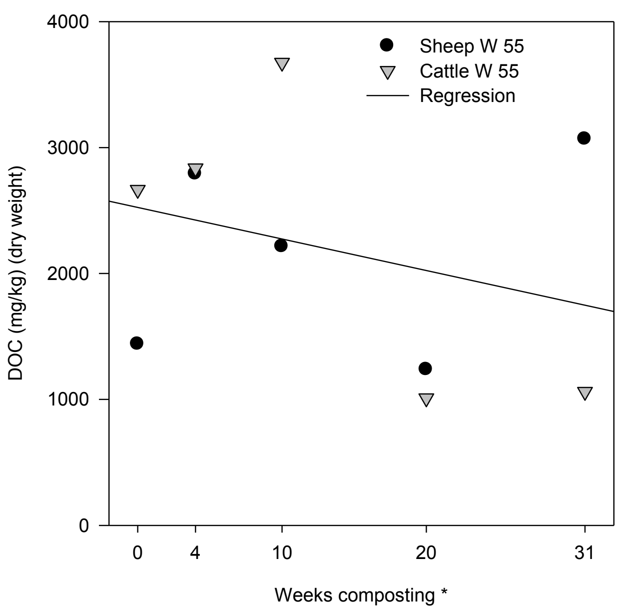


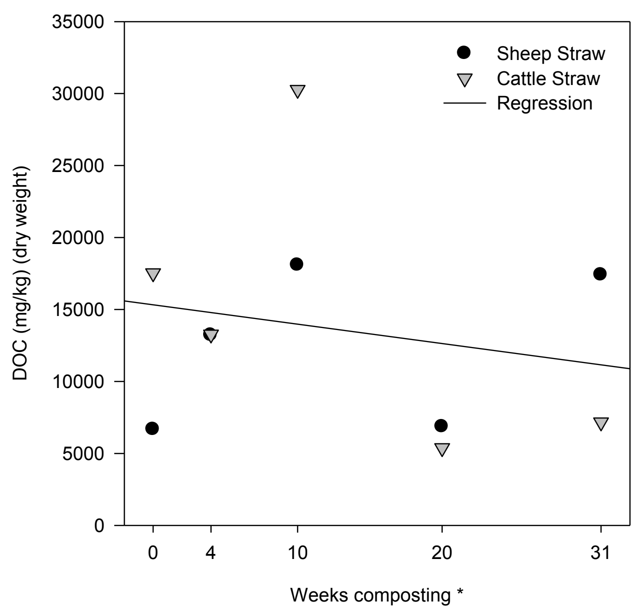
A7.7 Dissolved Organic Carbon (DOC)



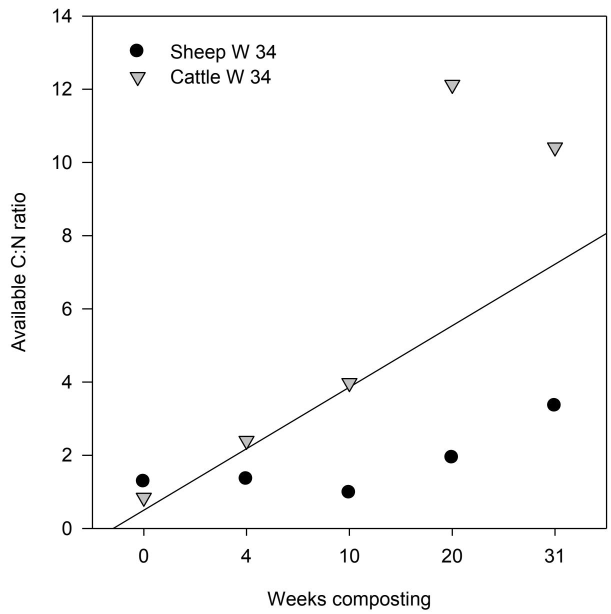


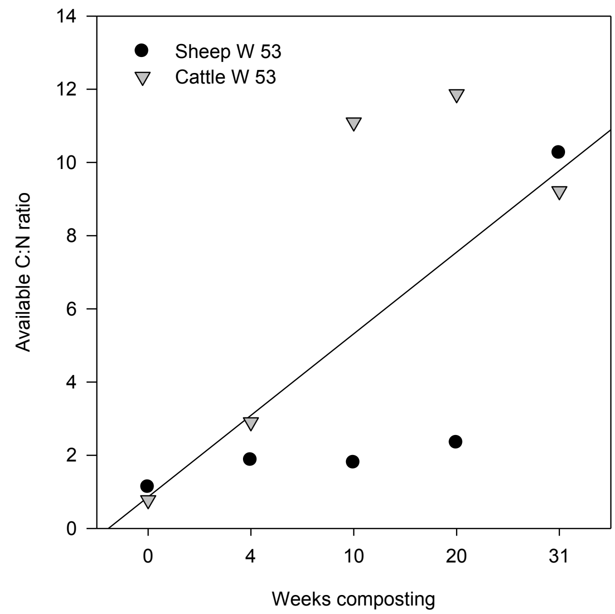
Treatment	Line equation	R^2	p. value
W34	$y = -47.112x + 2993.1$	$R^2 = 0.3396$	.302
W53	$y = -34.051x + 3040.6$	$R^2 = 0.2459$	.396
W55	$y = -25.009x + 2523.7$	$R^2 = 0.1857$	.469
Straw	$y = -134.43x + 15325$	$R^2 = 0.0664$	.676



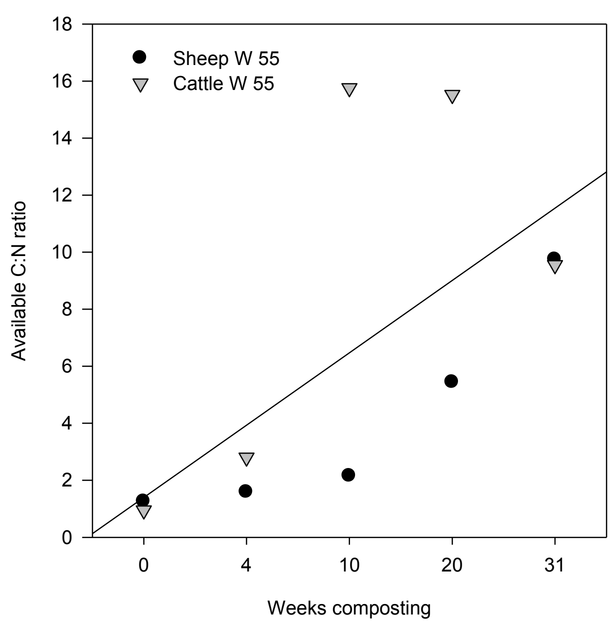


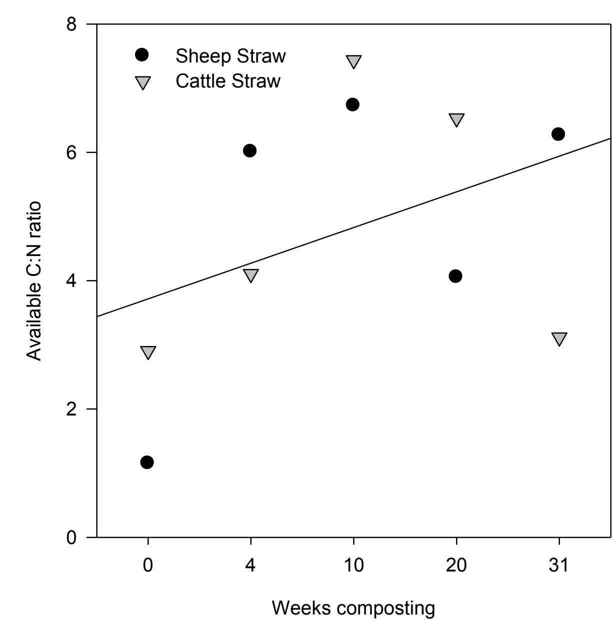
A7.8 Available C:N ratio



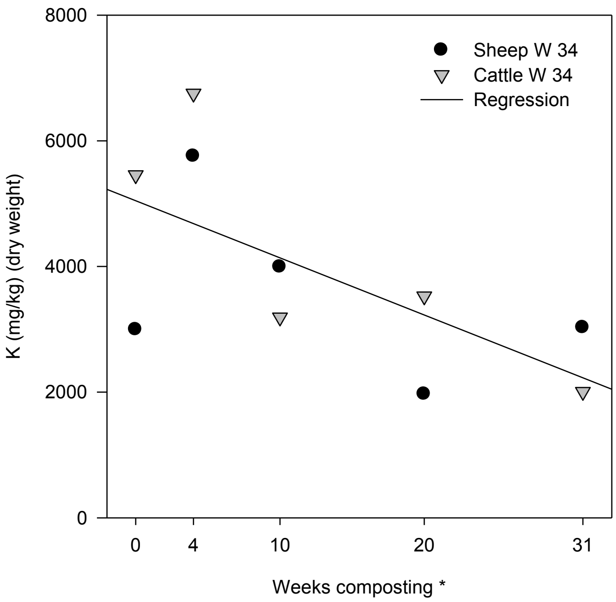


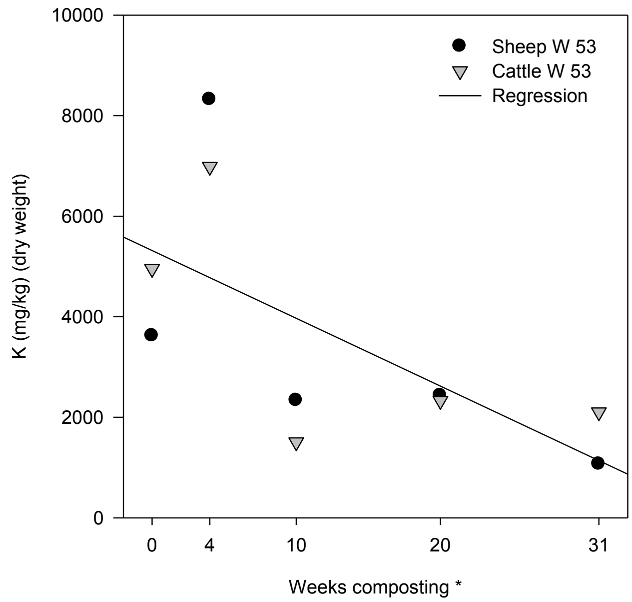
Treatment	Line equation	R^2	p. value
W34	y = 0.2136x + 1.0832	$R^2 = 0.8772$	**.019**
W53	y = 0.2719x + 1.7879	$R^2 = 0.9045$	**.013**
W55	y = 0.2943x + 2.6464	$R^2 = 0.6896$	.082
Straw	y = 0.0449x + 4.2461	$R^2 = 0.0963$	.611



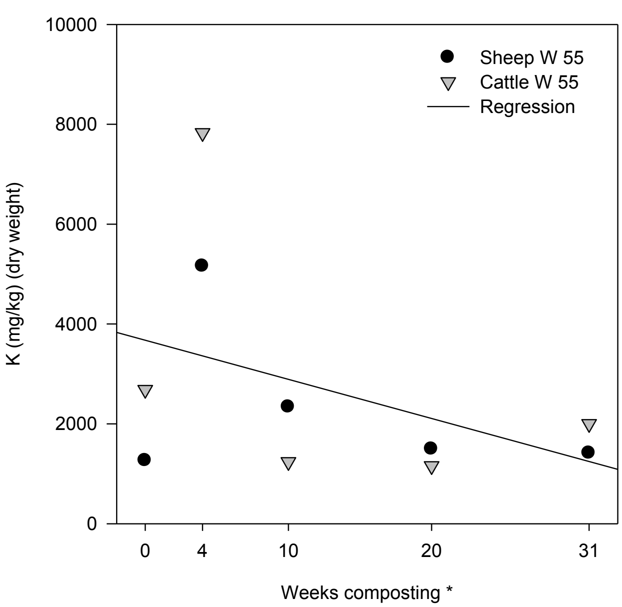


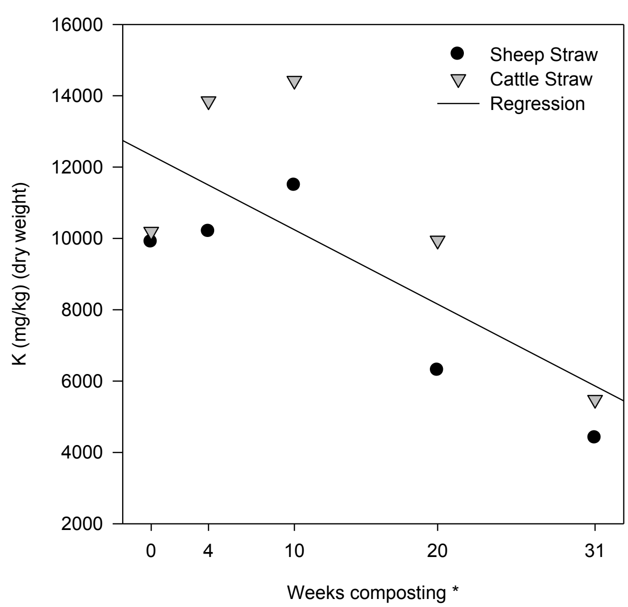
A7.9 Potassium (K)



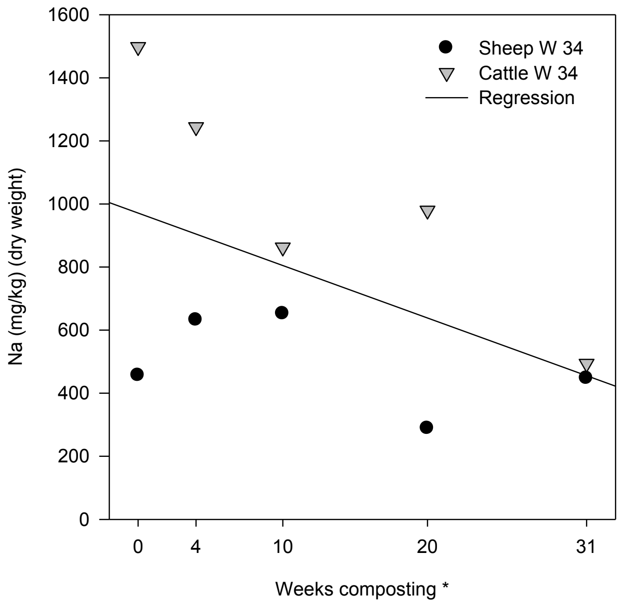


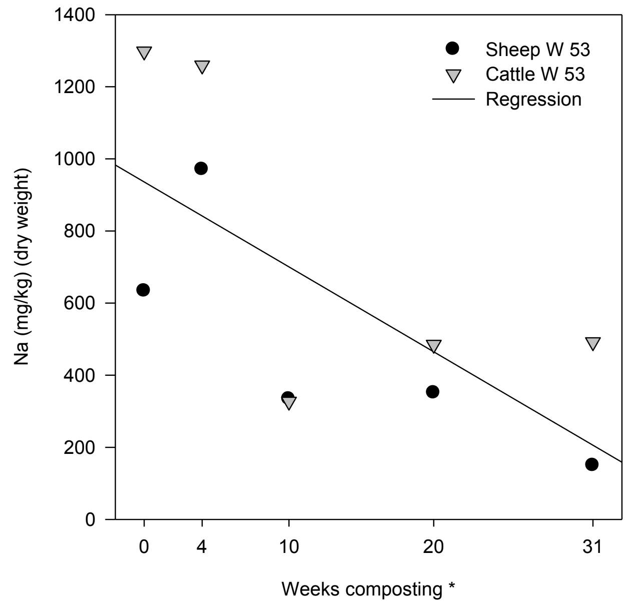
Treatment	Line equation	R^2	p. value
W34	y = -90.886x + 5046.7	$R^2 = 0.5815$	.134
W53	y = -134.79x + 5315.8	$R^2 = 0.4543$	.212
W55	y = -78.336x + 3674.8	$R^2 = 0.2083$	.440
Straw	y = -208.54x + 12327	$R^2 = 0.6672$	.091



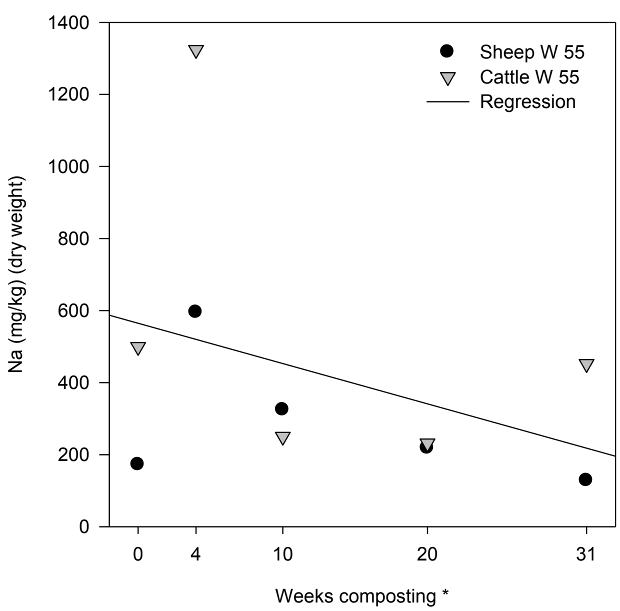


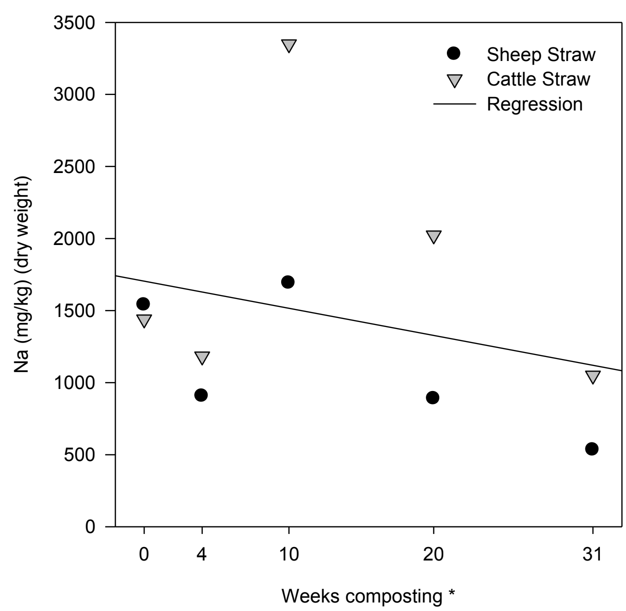
A7.10 Sodium (Na)



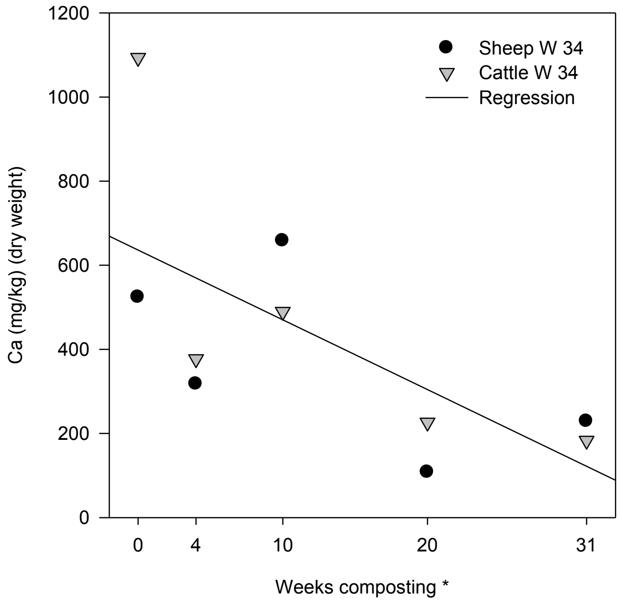


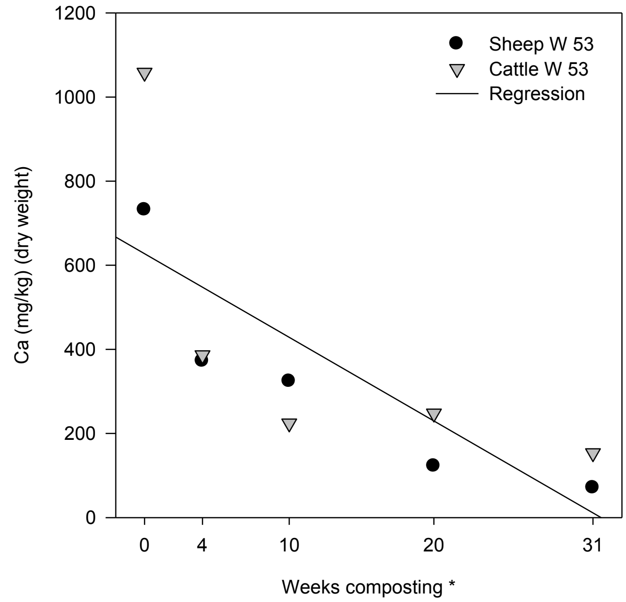
Treatment	Line equation	R^2	p. value
W34	y = -16.628x + 971.27	$R^2 = 0.9794$	**.001**
W53	y = -23.558x + 936.05	$R^2 = 0.6062$	.121
W55	y = -11.182x + 564.73	$R^2 = 0.2132$	.434
Straw	y = -18.804x + 1703.7	$R^2 = 0.1281$	.554



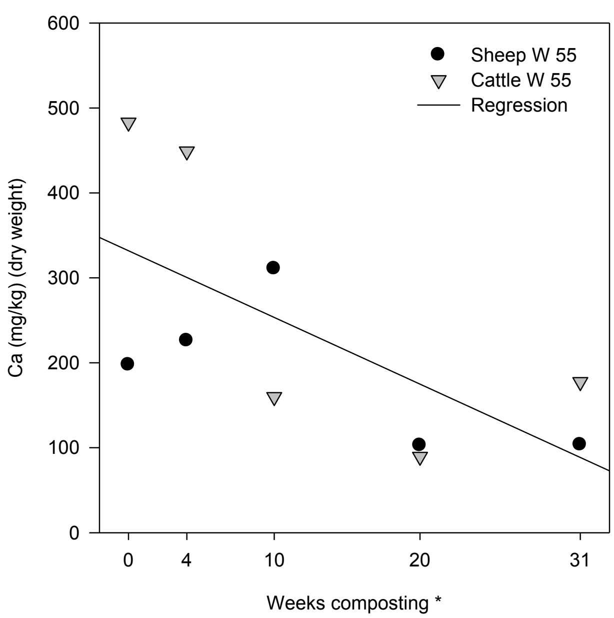


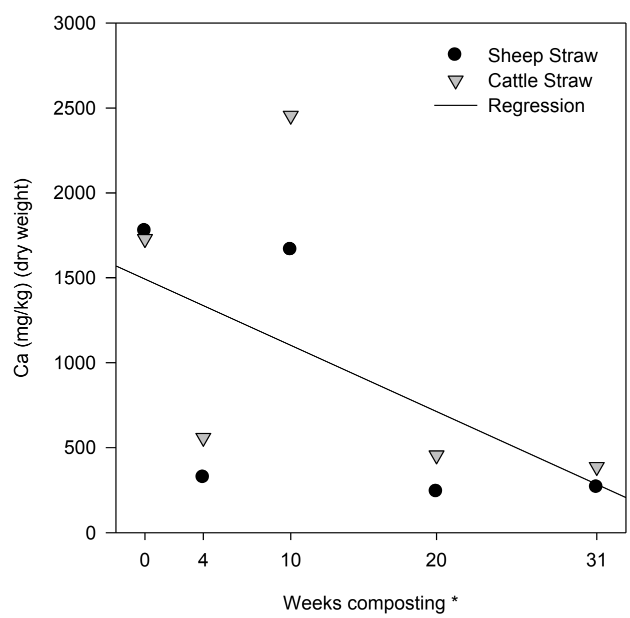
A7.11 Calcium (Ca)





Treatment	Line equation	R^2	p. value
W34	y = -16.584x + 635.97	$R^2 = 0.6000$	.124
W53	y = -19.864x + 627.15	$R^2 = 0.6470$	.101
W55	y = -7.8532x + 331.91	$R^2 = 0.7852$	**.045**
Straw	y = -38.931x + 1491.8	$R^2 = 0.3331$	.308





APPENDIX VIII

Appendix – VIII – The Woodchip for Livestock Bedding Project

To access to all the Woodchip for Livestock Bedding Project public releases (pdf.) go to:

http://www.hccmpw.org.uk/publications/farming_and_industry_development/alternative_bedding_for_livestock/

The candidate was the principle or sole contributor to the following titles listed on the webpage above:

- An assessment of woodchip compost
- Productivity of woodchip compost
- Woodchip compost – options for use
- Economic appraisal of woodchip use
- The Woodchip for Livestock Bedding Project (final report)