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The Potential for Utilising Disturbed and Contaminated Sites for the Production of Willow Short Rotation Coppice Forestry

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Er cof am Dadcu a Mamgu annwyl

Mr William Jones

'Will Typicca'

&

Mrs Lilwen May Jones

'Mam'

"A garwyd mewn bywyd, a drysorir mewn cof"

Also in memory of

Mrs Mary Campbell and Ollie

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DECLARATION

Except where specific reference is made to other sources, the work presented in this thesis is the original work of the author. It has not been submitted, in part or in whole, for any other degree.

Certain of the results have been published elsewhere.

Stephen Rees

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ABSTRACT

The utilisation of disturbed and contaminated sites for the production of willow (*Salix*) short rotation coppice forestry is an area of opportunity that has not been fully addressed. The significant areas of contaminated and disturbed sites in the UK that require remediation represent an opportunity for exploring alternative low cost remediation strategies. Conventional approaches to site remediation have involved costly engineered solutions, solutions which clearly cannot be afforded on all contaminated and disturbed sites. As an alternative to hard engineered solutions this thesis considers the potential to utilise these areas for the production of willow short rotation coppice forestry. The planting of these sites with willow provides a potential income stream through the sale of the biomass produced. In addition willow short rotation coppice forestry provides many additional benefits to these sites such as their ability to absorb heavy metals, provide fast site enhancement and stabilisation, act as a carbon sink and as a potential route for the recycling of organic matter.

Current knowledge and experience of willow short rotation coppice forestry has been gained from its production on agricultural land. As part of this research a field trial was established on a capped former steelworks site to quantify the ability of contaminated and disturbed sites to successfully establish and promote the growth of willow. The silvicultural practices employed to grow willow Short Rotation Coppice were considered to assess their impact upon the survival and biomass produced at the end of each growing season, and specifically to consider whether adopting different management techniques were beneficial in growth conditions associated with disturbed and contaminated sites. The silvicultural practices considered in this field trial were the addition of fertiliser, the use of herbicide, rotation length before coppicing (1, 2 or 3 Years) and planting density (0.5 m and 1.0 m). In addition a further 18 clones were screened to consider their ability to establish and survive in such harsh growing mediums.

Results have indicated considerable variability within the field trial, which may be indicative of the heterogeneity of the growing medium. The main silvicultural practice in

the field trial that influenced survival and growth was weed control. All other silvicultural practices used were considered to have less influence on the survival and growth of the willow. Yields obtained from willow short rotation coppice forestry grown on disturbed and contaminated sites fail to compare with those grown on the higher grades of agricultural land. On contaminated and disturbed sites however, survival rather than biomass yield is viewed as the key issue to ensure that ground cover is established.

Work undertaken by the Water Research Council to assess the potential of a rapid screening technique for willow establishment and survival on metal contaminated sites is replicated and expanded to other clones of willow and heavy metals. The results obtained from this quick and simple leaf disc screening trial would in the first instance seem to indicate that the leaf damage suffered by leaf discs obtained from differing clones of willow to be consistently more pronounced amongst individual cultivars. Limitations are imposed upon this quick screening test by the lack of available information to allow comparison of these screening trials with information for willows established in growing mediums of a similar metal contamination.

To fully appreciate the value of growing willow on disturbed and contaminated sites it is considered that the economic equation should be readdressed and that the value of additional opportunities/ benefits are included if the true value of utilising these sites for its production is to be demonstrated. Studies to identify the non-marketable benefits for woodlands and energy crops grown in Sweden are used to give an indication of the true economic value of growing willow SRC on disturbed and contaminated sites, and are used to provide an insight into the economic value that can be attributed to the social and environmental benefits of willow production.

CHAPTER 1 - THE RECLAMATION AND RESTORATION OF DISTURBED AND CONTAMINATED INDUSTRIAL SITES

1.1 Introduction

The implementation of The New Contaminated Land Regime: Part IIA of the Environmental Protection Act 1990 (EPA, 1990) has placed a statutory obligation upon all local authorities (Glasgow City Council, 2004) in the United Kingdom

"to cause its area to be inspected from time to time for the purpose of identifying contaminated land" s.78B(1) IIA EPA, 1990.

Contaminated land has been defined in this legislation as

"land which appears to the Local Authority to be in such condition, by reason of substances in, on or under the land, that significant harm is being caused, or is likely to be caused"s.78A(2) 11A EPA 1990.

It is apparent that the ability to identify these sites would be a major step forward towards addressing the issues associated with them. Estimates of the extent of contaminated sites have ranged between 100,000 ha and 300,000ha in the UK alone (Holgate, 2000). Surveys undertaken of disturbed industrial land, land incapable of use without prior remediation or reclamation activity, have identified in Scotland alone approximately 12,000ha of such land (Scottish Office, 1990), with England and Wales having an additional 40,000ha (DOE, 1994).

1.2 Background History to the Restoration and Reclamation of Disturbed and Contaminated Industrial Sites

Prior to the introduction of The New Contaminated Land Regime: Part IIA of the Environmental Protection Act 1990, the driving force behind most reclamation projects undertaken was as a consequence of policy developments to address both environmental and spatial planning issues such as the need for land for new housing and industry (van Veen et al., 2001). Historically the stimulus for such projects was very different indeed.

The degradation of the environment by heavy industries in the past might have been regarded as a worthwhile price, albeit a high price, of economic survival (Richards et al., 1993). Reclamation and rehabilitation of former industrial sites initially only received a trigger as a consequence of events of a local significance. In the Ruhr valley in Germany, changes to the industrial structure through the rapid contraction of heavy industry resulted in locally magnified environmental degradation, and with it the stimulus to put in place a remediation strategy (Richards et al., 1993).

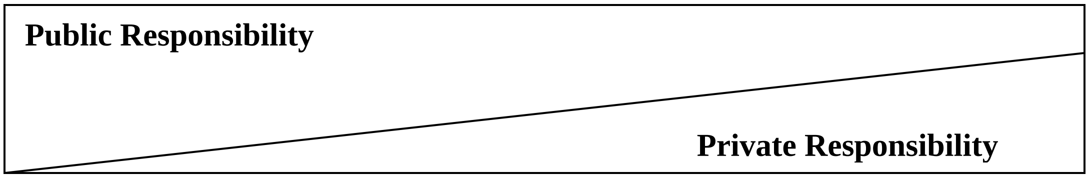
In the United Kingdom an early stimulus was not on environmental grounds but rather on the grounds of public safety (Richards et al., 1993). A rude awakening to the need to make safe, sites occupied by colliery spoil was delivered to the people of Wales and the UK on the morning of 21st October 1966. A period of heavy rainfall had resulted in the destabilisation of a colliery spoil perched high above the village of Aberfan, South Wales. The resulting slide of spoil engulfed a primary school and several houses. The death toll totalled 144, the majority of these primary school children. The resulting public outcry resulted in the passing of legislation to ensure that tips were made safe. Safety was very much the initial concern, however the authorities were soon to realise that land created as a result of safety measures could be made available to attract new industries and housing.

Today the approach to land reclamation and remediation encompasses wider issues. No longer are such sites purely addressed as a problem requiring a solution but rather a more integrated holistic approach is taken when considering contaminated sites, such as their use to formulate solutions that will also meet the needs of society (van Veen et al, 2001). Since legislation was first enacted in the UK in the 1960's, responsibility for addressing such problems has gradually shifted from a near total public responsibility towards a greater responsibility by individuals and private and commercial enterprises. This evolution is clearly summed up in Figure 1.1 which shows the changing objectives behind the need to address derelict and contaminated land in England in Wales from the 1960's to the early 1990's. Also shown in the top section of Figure 1.1 is that over time responsibility for addressing these issues have shifted from the public to the private sector

The responsibility of private individuals and organisations is further enshrined in the Contaminated Land Regime and more recently in the Urban Regeneration Companies (URC) established as a result of a Government White Paper on Urban Renewal (DTLR, 2000). These URC have been promoted by the government, and established by local partners, in order to achieve a focused, integrated regeneration strategy for key towns and cities. Their aim is to produce a powerful and coherent single vision for the future of their entire area and then co-ordinate its implementation.

Initial concerns on land remediation focused heavily upon colliery spoil. The varied nature of our former industrial activities, ranging from mining and quarrying through to industrial works producing and utilising a variety of inorganic and organic chemicals in their industrial processes, presents us today with numerous problems.

There is available to us today a variety of technologies to address the problems of contamination and to potentially remediate these sites. Constraints are always apparent to each solution; as such any remedial approach or reclamation strategy adopted must take into account the objectives of reclamation at any particular site.



Objective	Disciplines Involved	Period	Legislation
Physical Safety	Engineers	1966	Mines and Quarries (Tips) Act 1969
Industrial Regeneration And New Housing	Engineers and Architects	1970	Mines and Quarries (Tips) Regulations 1971
Sports Facilities and Amenities Containment of Pollution Landscape Improvement	Engineers, Architects, Landscape Architects, Ecologists and Soil Scientists	1980	Control of Pollution Act 1974
Urban Renewal and Rural Support Control of Pollution Prevention of Pollution Treatment of Pollution	Engineers, Architects, Landscape Architects, Ecologists and Soil Scientists, Industrial Archaeologists, Chemists/ Biologists, Hydrogeologists, Surveyors and Lawyers	1990 1993	Derelict Land Act 1982 Town and Country Planning (Assessment of Environmental Effects) Regulations 1988 Environmental Protection Act 1990 Water Resources Act 1991

Figure 1.1 The Evolution of the Approach to Derelict and Contaminated Land in England and Wales (Richards et al., 1993)

1.3 The New Contaminated Land Regime: Part IIA of the Environmental Protection Act 1990

Undoubtedly the legacy of our past industrial activities represents a huge challenge for future generations providing a threat to sustainable development, through as Holgate (2000) states:

- Depriving people of a clean and healthy environment
- Damaging the wider environment and wildlife
- Putting pressure on Greenfield sites and on our soil resource by failing to recycle previously used land; and
- Placing a large burden on those responsible for remediating sites, both private companies, individuals and the economy as a whole.

Implementation of the New Contaminated Land Regime represents the first step towards addressing nationally the concerns raised by contaminated land. All local authorities in Scotland, Wales, Northern Ireland and England were required to produce a written strategy for identifying the contaminated land in their area, and thereafter put in place measures to prioritise sites for remediation and clean up.

In undertaking the inspection of its area each local authority needed to determine whether any sites within its boundaries were contaminated and then act as the enforcing authority for all sites other than those designated as ‘special sites’ (due to the nature of the contamination) and seek to (Holgate,2000) :

- Establish the ‘appropriate person or persons’ responsible for the remediation of the land.
- Provide consultation as to what level of remediation will be required and ensure that this occurs either through agreement with those concerned or through the

issuing of a ‘remediation notice’. In some instances the local authority may undertake the work themselves.

- Determine who should be liable for the costs
- Provide a record of their regulatory action on a public register i.e. record certain prescribed information.

Each local authority is responsible for ensuring that all contaminated sites within its area are remediated in accordance with the statutory guidance and utilise the concept of a ‘pollutant linkage’ i.e. a source, pathway receptor principle to determine the need for a remediation strategy. Priority will be given to those sites where a reasonable possibility of a pollutant linkage exists and the level of remediation will be dependent upon the ‘suitable for use’ approach whereby the level of remediation will be suited to the end use of a site based upon a risk assessment and a cost benefit analysis.

Given the extent of the contaminated land in the UK there will be placed upon local authorities the need to consider all remediation options available to it. These may take the form of a hard engineered solution, providing an expensive but relatively quick remediation. Such approaches might be deemed suitable for small areas of land only. Alternatively some form of soft stabilisation approach may be adopted, which may not provide a quick solution to a contaminated site’s problem but may ensure containment and site stabilisation at reduced cost. Such an approach is usually suited for those large contaminated areas with no immediate commercial opportunities. One such opportunity would be to utilise these sites for the production of willow (*Salix* spp.) Short Rotation Coppice (SRC).

1.4 Guidelines Used to Determine Whether Land is to be Classed as Contaminated in the UK

Prior to 2002, assessment of contaminated land in the UK used as a reference point values published in a Department of the Environment technical document to help assess land contamination. This document known as the ICRCL Guidance Note 59/83 (ICRCL,

1987) was originally prepared by the Inter-Departmental Committee on the Redevelopment of Contaminated Land (ICRCL).

ICRCL 59/83 provided “trigger values” and “threshold values” for a series of substances commonly found in contaminated land. Soil contaminant values exceeding those published values set in the guidance note were deemed to require treatment before a stated land use could proceed. Trigger values were published in relation to the stated end use, with lower concentration values being given for gardens in residential housing as opposed to public open space. Threshold values also took into consideration the affect of metal concentrations on the ability of plants to establish and grow in heavily contaminated soils. Values exceeding the threshold given in the guidance note were deemed to be phytotoxic to plant growth. Selections of these values are reproduced in Table 1.1.

Table 1.1 ICRCL 59/83 “trigger values” and “threshold values” for a series of substances commonly found in contaminated land. (ICRCL, 1987)

Contaminant	**Planned Use**	**Trigger Values** (mg / kg^{-1} air-dried soil)	
Group A (may pose hazards to health)		Threshold	Action
Arsenic	Domestic gardens, allotments	10	-
	Parks, playing fields, open space	40	-
Cadmium	Domestic gardens, allotments	3	-
	Parks, playing fields, open space	15	-
Chromium (hexavalent)	Domestic gardens, allotments	25	-
	Parks, playing fields, open space	No Limit	No Limit
Chromium (total)	Domestic gardens, allotments	600	-
	Parks, playing fields, open space	1,000	-
Lead	Domestic gardens, allotments	500	-
	Parks, playing fields, open space	2,000	-
Mercury	Domestic gardens, allotments	1	-
	Parks, playing fields, open space	20	-
Selenium	Domestic gardens, allotments	3	-
	Parks, playing fields, open space	6	-
Group B (Phytotoxic - but not normally hazardous to health)		Threshold	Action

Copper	Any uses where plants are grown	130	-
Nickel	Any uses where plants are grown	70	-
Zinc	Any uses where plants are grown	300	-

In response to a House of Commons Select Committee on the Environment report, the Department of the Environment initiated research to develop a scientific framework for assessing the risk to human health from land contamination. The initial outputs of this research programme were published in 2002 (DEFRA, 2002; DEFRA and EA, 2002). Within the published package of the research programme, there were four main reports (Contaminated Land Reports (CLR) 7, 8, 9 and 10) and supporting toxicology reviews and Soil Guideline Values (SGV) for individual substances. Individually these reports are –

- CLR 7: Assessment of risks to human health from land contamination. An overview of the development of guideline values and related research.
- CLR 8: Potential contaminants for the assessment of land.
- CLR 9: Contaminants in soil. Collation of toxicological data and intake values for humans.
- TOX: Toxicological reports.
- CLR 10: The Contaminated Land Exposure Assessment (CLEA) model. Technical basis and algorithms (includes software).
- SGV: Soil Guideline Values.

Together these reports, toxicology reviews and SGVs are considered to represent the main instruments to be used when assessing the human health risks from land contamination in the UK, and are deemed to provide a coherent and consistent approach for assessing risk.

The CLEA model is used to provide an assessment of risks to human health from soil contamination and is based upon:

- Toxicological criteria that establish a level of unacceptable human intake of a contaminant derived from the soil.
- An estimation of human exposure to soil contamination based on generic land-use, taking into account the characteristics of adults and children, their activity patterns and the fate and transport of the contaminant in soil

Soil Guideline Values for individual contaminants are published (as previously in ICRCL Guidance Note 59/83). They are deemed to be generic assessment criteria and are to be used as indicators for "intervention" either in the form of further detailed risk assessment and/ or remediation. SGV do not exist for all contaminants, their use is intended solely as a tool to be used in the process of risk-based management of sites and are intended to encourage a transparent and consistent approach, by focusing resources on situations that require more detailed assessment and action. Where no SGV exists a risk assessment of site –specific criteria is deemed the appropriate model for action and should be used to inform the decision-making process.

1.5 Treatment Technologies Currently Employed for the Restoration and Remediation of Contaminated and Disturbed Industrial Sites

Treatment options available for dealing with contaminated land will be dependent upon the nature of the contaminants present, the degree of contamination and its influence upon surrounding receptors. Before any strategy can be implemented a risk assessment will need to undertaken of a suspected site to define-

- The problem
- The extent of the problem
- The impact of the problem

The first stage in this approach would be to conduct an initial review or preliminary investigation of a site to include information on such issues as site history, potential sources of contamination together with any visible evidence of contaminants present together with details of existing land uses and potential sensitive receptors (Scottish Enterprise, 1994, DTI, 2000). Should the review conclude that there is a significant reason to believe there to be contamination on a site, this will warrant the further commissioning of a more intrusive site investigation to record the levels and locations of any contaminants present. It is only when all data have been gathered and a risk assessment undertaken that any attempt at putting together a remediation strategy should be undertaken. It is only when all parties involved are satisfied of the need to remediate a site that an appropriate treatment technology can be employed.

The options for treatment (Scottish Enterprise, 1994, Martin and Bardos, 1996) can be divided into three options namely those of

- Containment
- Separation, or
- Destruction.

Within these three options the treatment process may be termed as being physical, biological or chemical in terms of the remediation process. Within the treatment option of containment is included the use of landfilling as a solution to remediating contaminated and disturbed sites. Such an operation may be undertaken both *in-situ* and off-site however its value as a treatment process can be questioned, as such an operation merely moves the problem from one area to another without truly providing for the remediation of contaminated or disturbed sites.

All treatment technologies are referred to as being in situ or ex situ, ex situ referring to treatment processes applied to excavated soil either on site or off site. Choosing between an in situ and ex situ solution will require consideration of the remedial problem. *In-situ* solutions are on the whole considered less damaging to the soil structure and fertility requiring less site disturbance. *Ex-situ* solutions are likely to be more beneficial where a more rapid and controlled process is required.

Biological treatments are effective primarily for organic contaminants, not heavy metals and rely on the four processes of biodegradation, biological transformation, biological accumulation or immobilisation of contaminants to achieve treatment of a contaminated soil. Commercial processes operating biological treatment options often rely upon biodegradation to remediate sites. Technologies that employ such a remediation process have included biostimulation or bioaugmentation (Martin and Bardos, 1996), in these technologies nutrients, oxygen and moisture are added to enhance the processes of naturally occurring bacteria. Bacteria specifically prepared to speed up biodegradation rates can also be utilised in the remediation process. Examples of the technological processes employed have included:

Biopiling- an *ex-situ* process whereby contaminated soil is constructed into engineered piles or cells with the aim of enhancing conditions required for biodegradation through greater control of oxygen, nutrient such as phosphorus and nitrogen and water.

Bioventing - a process which stimulates the natural *in-situ* biodegradation of degradable contaminants in the unsaturated zone (above the water table). Air is supplied *in- situ* at low flow rates to oxygen deprived soil microorganisms therefore stimulating biodegradation and minimizing the volatolisation of volatile organics into the atmosphere.

Biosparging - an in situ remediation technology that exploits and stimulates indigenous microorganisms to degrade organic contaminants in saturated soil. Air is injected into the saturated zone (below the water table) to increase the activity of the soils indigenous microorganisms through increased oxygen dissolution. The increased oxygen enhances aerobic biodegradation of the contaminants present in the soil or groundwater

Ex-situ examples of a biological treatment process are commonly referred to as landfarming or composting.

Chemical processes rely upon the chemical reactions of oxidation, reduction, immobilisation, and extraction. Most of these processes are likely to occur *ex-situ*, such as soil washing, a technique that separates and cleans contaminated soils either physically or chemically. Initially the contaminated soil is screened to remove oversize material which can then be treated separately for reuse. The contaminated soil is then passed into a Soil Scrubbing unit. A water wash is fed into the unit which contains detergents to adjust the pH and remove organics and heavy chemicals.

Soil flushing treatments have been applied commercially *in-situ*. This process involves the extraction of contaminants from the soil with water or other suitable aqueous solutions. Soil flushing is accomplished by passing the extraction fluid through *in-situ* soils using an injection or infiltration process. Extraction fluids are recovered from the underlying aquifer and, when possible, they are recycled.

Physical approaches to treating contaminated soils often employ such treatments as soil washing and soil vapour extraction and electroremediation. These processes often rely upon the physical differences between a soil and the contaminant e.g. volatility or for example differences in density between contaminated and uncontaminated soil particles.

Solidification and Stabilisation technologies whilst different are usually employed as a combination of both treatments. Solidification employs chemical agents to interact with contaminated soil to produce a mass with enhanced structural integrity and reduced permeability (Martin & Bardos, 1996). Stabilisation technologies again employ chemical agents, however in this instance they are employed to react with the contaminated soils and reduce their mobility or convert them into a less toxic form. Vitrification, whilst related to solidification as contaminants are rendered immobile, is achieved through high thermal temperatures and as such may also be classed as a thermal process.

Thermal processes often rely upon raised temperatures to remove, destroy and immobilise by either volatilising, incinerating or vitrifying the contaminants. Steam stripping is an option that is often employed on site whilst incineration often requires location at a central treatment facility.

It is unlikely that any two sites will incur the same remediation costs. The cost of treatment will be highly dependent upon local circumstances. As a guide to costs involved in contaminated land remediation the table below provides an indicative comparison of costs involved.

Table 1.2 Comparison of Typical Costs for a Range of Remediation Techniques (DTI, 2000)

Technique	Range of Costs
Bioremediation	£1-50/ m^3
Stabilisation/ Solidification	£10-100/ m^3
Soil Washing	£15-40/ m^3
Barrier/ Encapsulation	£20-180/ m^3
Landfilling	£30-75/ m^3
Incineration	£100-400/ m^3

Prior to the implementation of any of the remediation technologies noted above there will be a requirement for a cost benefit analysis of likely costs against the benefits of implementing a strategy. Given the area of contaminated land in the UK all treatment options may be considered as being appropriate at some time or other. In an ideal world it could be argued that both the finance and resources should be made available to rectify all sites degraded as a result of the activities of man. In reality advantage must be taken of all opportunities that might prevail, one such opportunity might be the potential to use contaminated sites for the production of willow short rotation coppice.

The utilisation of disturbed and contaminated sites for the production of willow short rotation forestry represents an opportunity to bring sites with little or no opportunities back into a commercial operation (Licht and Isebrands, 2005; Vandenhove et al., 2001; Rockwood et al., 2004). Willow biomass produces a marketable commodity, however the benefits of its use in site enhancement and stabilisation, reducing leachate runoff and the potential to uptake heavy metals make the opportunities associated with its growth worthy of consideration. Compared with engineered solutions to disturbed and contaminated sites the growth of willow is a low cost remediation strategy (Pulford and Watson, 2003; Dickinson, 2000). However, its use is presented in the context of this thesis as an alternative solution to those sites with limited possibility of securing funds for clean up.

1.6 Willow Short Rotation Forestry

Short Rotation Forestry, more often referred to as Short Rotation Coppice (SRC), is a form of forestry used to produce large volumes of wood biomass over a relatively short period of time. It is often referred to as a form of agroforestry due to the practice of growing SRC on arable land. However, its origins are very much based within the forestry sector. It is important to forget our traditional concept of wood being grown for quality timber used in construction and for furniture manufacture. SRC is grown purely for the volume of wood it can produce over relatively short periods of time.

Willow, or to give its correct name the genus *Salix*, is a member of the Salicaceae family. Newsholme (1992) noted there were 400 species of willow, with more than 200 listed hybrids. Active breeding programmes have been undertaken in recent years in both Sweden and the UK with many new clones and hybrids of willow being introduced (Ahman and Larssson, 1994; MacPherson, 1995; Larsson, 1998).

The use of coppice willow as spindling material and for basket weaving has been associated with the more conventional practice of coppicing that employed longer growth cycles for the willow prior to coppicing (MacPherson,1995). Growth cycles typically employed could be as long as 12-15 years and more commonly might have included a mixture of species.

Willow SRC grown under today's agroforestry practices have growth cycles that are characterised by shorter growth cycles (less than 5 years) and are utilised as a source of fuel in biomass energy boilers/ plants or as the raw material for the production of chipboard or medium density fibreboard (MDF) (MacPherson,1995).

Unrooted cuttings approximately 20-25cm in length with a diameter of 8-15mm commonly referred to as a *stool,* are collected during the winter months for planting in early spring. Two thirds of the length of the stool is placed below the ground level with the remaining third being above ground level. The process is described graphically in figure 1.2. Planting densities of 10,000 stools/ ha and above are not unusual (Bullard et al., 2002). After one year of growth it is normal practice to 'coppice' or cut back the initial stem growth to encourage multiple shoots and hence increased biomass. In a commercial environment the practice of *beat-up* is employed on willow plantations after one year's growth. This term refers to the process of replanting and replacing dead stools. After a further growing period of 3 to 5 years the willow can be periodically harvested over a lifespan of 25-30 years (Larsson, 1997). The average annual production of wood biomass from an established and well managed willow plantation can be in excess of 12 tonnes of dry matter per hectare (Beale & Heywood, 1997) however new clones and optimal potential production in southern England has given the possibility of yields of 20 t ha^{-1} of dry stem wood annually (Nixon et al., 2001).

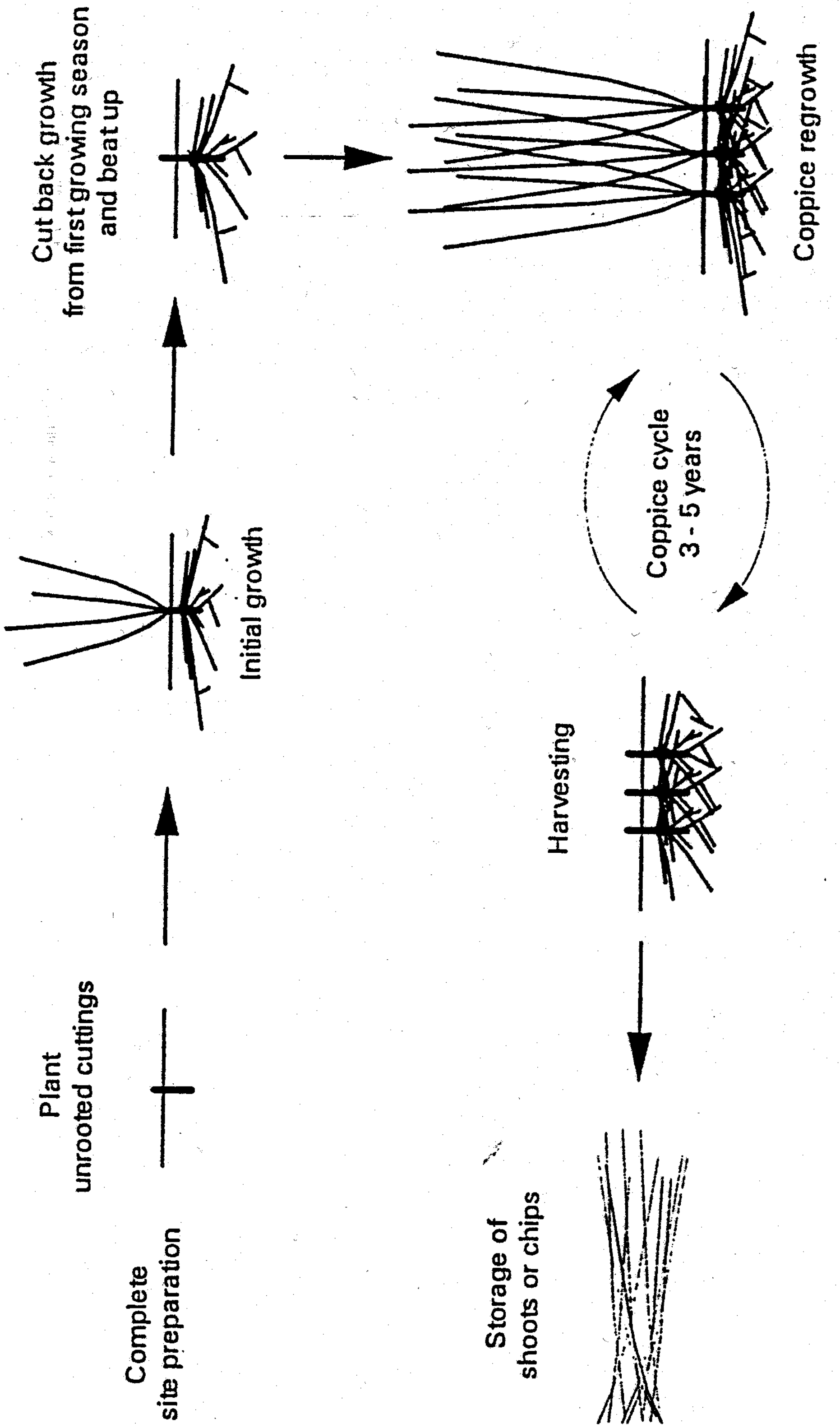


Figure 1.2 Diagram of the Short Rotation Coppice System (Mitchell et al., 1993)

The whole process is often today referred to as a form of agricultural forestry arable energy as opposed to a true forest industry in the traditional sense as the management practices required for its growth in terms of site preparation, weed control, fertilisation and harvesting have more similarities to those used in arable farming than in forestry. Indeed many of the practices and machinery currently employed in the production of arable crops such as wheat, barley and some of the root vegetables have been demonstrated to be readily adaptable by the agricultural sector for the planting and growth of SRC.

Establishment costs associated with the willow SRC within the UK are difficult to establish given the few commercial operations and the limited number of growers (B9 Energy Ltd, 2002). Indicative costs for a plantation density of 15,000 ha^{-1} have been suggested to be in the region of £1,700-1900 ha^{-1} in the UK compared with £700-900 ha^{-1} in Sweden where the industry is considered to be more effective and established (B9 Energy Ltd, 2002). A breakdown of costs for the establishment of willow SRC is given in Table 1.3.

Table 1.3 Establishment Costs Associate with Growing Willow SRC in the UK (B9 Energy Ltd, 2002)

Operation	Costs £ ha^{-1}
Fencing	370
Cultivations	90
Planting & Materials	1100
Weed Control	150
Cutting Back	50
Total Cost ha^{-1}	1764

As an indication of the expected income that could be derived from willow SRC woodchips comparison can be made with woodchips derived from sawmills that have an average delivered price of £37.9/ odt. (B9 Energy Ltd, 2002). Alternative financial support mechanisms for this fledgling industry in the UK are limited to the Woodland Grant Scheme (WGS) and Arable Aid Scheme for setaside land. Indirectly support is offered to this industry from the electricity production and supply industries where government legislation exempts electricity produced from renewable energy technologies from the levy imposed on energy derived from fossil fuels (Levy Exemption Certificates) and upon the electrical supply industry who are obligated to purchase a percentage of their energy supply from renewable sources (Renewable Obligation Certificates).

1.7 Using Willow Short Rotation Coppice to Phytoremediate Contaminated Sites

The potential for utilising willow, a non-food crop, to remove contaminants in situ from contaminated sites has seen significant research interest. (Pulford, 1995, Dickinson et al., 2000, Pulford and Watson., 2003, Vervaeke et al., 2003, Vandenhove et al., 2002, Laureysens et al., 2004, McGrath et al., 1993, WRC, 1993, Punshon & Dickson, 1997, Cunningham et al., 1995, Pulford and Dickinson, 2005, Rosselli et al. 2003). The use of plants to remove pollutants from the environment and to render them harmless is defined by Salt et al. (1998) as phytoremediation. Phytoremediation can be further sub-divided into five main subgroups (Pulford and Watson., 2003). These are referred to as:

- Phytoextraction – the removal of metal contaminants from the growing medium and concentration in the plant above ground biomass (Kumar et al., 1995)
- Phytodegradation – the degradation of organic pollutants by plants and associated microbes (Burken and Schnoor, 1997)
- Rhizofiltration – the absorption of metals from water by plant roots (Dushenkov et al., 1995)
- Phytostabilisation – the use of plants to immobilise or reduce the mobility of pollutants (Vangronsveld et al., 1995)
- Phytovolatisation – the use of plants to release pollutants into the atmosphere (Burken and Schnoor, 1999).

Baker et al, (1993) suggested using hyperaccumulators to remove metals from the growing medium. These plants were known to be capable of accumulating potentially phytotoxic elements in concentrations greater than 100 times than those found in non-accumulators (Salt et al., 1998). Whilst such species have been identified (Brooks et al., 1979) they have seldom exhibited a high biomass production level and are endemic to certain global areas only, making their potential for widespread use limited (Baker et al., 1993).

Willows are not considered to be hyperaccumulators, however their greater than average ability to take up metals does ensure that they may be termed as high accumulators when compared to “normal” plants (Greger and Landberg, 1999).

To be a successful phytoremediator, plants must be able to establish themselves rapidly in nutrient-poor contaminated soils and be able to remove metals from this growth medium whilst demonstrating that they are genetically stable as a consequence of having high concentrations of metal(s) in their plant tissue (Punshon et al., 1996). To be effective, plants must transport the metal(s) from the roots to the shoots i.e. the above ground parts, for ease of harvest and export from the site and produce relatively large amounts of biomass per unit of area. (Greger & Landberg, 1999, Punshon et al., 1996). An alternative benefit is also proposed for the use of willow for phytoremediation (Punshon et al,. 1996) whereby willows that survive in contaminated soil with minimal interaction and uptake of contaminants could be viewed as a benefit where mobilisation of contaminants into the wider environment and food chain require to be limited.

Willows offer significant benefits over other plants in that they provide a potential end use for the plant tissue and hence a possible income stream given their large production of biomass in a relatively short period of time. Their wide geographical distribution (Maccpherson, 1995), ease of propagation, coppicing ability and potential to produce high yields of juvenile growth are all factors that have ensured that willow SRC is considered an appropriate species for use in the remediation of contaminated and disturbed sites (Bending and Moffat, 1997; Bending and Moffat, 1999).

Conventional approaches to the remediation of contaminated sites such as soil washing, acid extraction, electrokinetic remediation are destructive to soil fertility and structure (Greger & Landberg, 1999), and can produce contaminated residues requiring further treatment or disposal to landfill. Utilising contaminated sites for the production of willow biomass on the whole is not destructive to soil fertility (Sennerby-Forsse, 1997) and should assist in developing healthy sustainable soils at brownfield sites (Dickinson et al., 2000).

Interest in the growth of willow on contaminated land has focused on its ability to absorb heavy metals into its plant tissue and hence assist in the removal of contamination from the growing medium (McGregor et al, 1995; Riddell-Black et al., 1997).

Whilst the levels of metal uptake in willow may be regarded as small and occurring over a relatively large time scale it is clear that their potential use to remediate over a long time scale and at a relatively low cost is possible (Dickinson and Pulford, 2005; Pulford and Watson., 2003; Klang-Westin et al., 2002; Laureysens et al. 2004). Bernedes et al., 2004 calculated a harvest of 20g Cd ha^{-1} year^{-1} by *Salix* viminalis on a site with a moderate yield of 10t DM ha^{-1} year^{-1}. Dickinson and Pulford (2005) note that where the concentration of cadmium in soils is marginally above guideline levels, the potential of willow to provide a cost-effective method of decontamination may be worthy of consideration, however, unrealistically long time scales would deter the use of willow to clean up highly contaminated sites.

Research into the use of willow SRC to uptake metals from contaminated soils is well recorded (Greger & Landberg, 1999, 1994; Riddell-Black, 1993; Erickson and Leddin, 1999; Pulford et al., 2002). These studies have looked at both field and laboratory experiments to consider the uptake of metals by willow. Different patterns in heavy metal behaviour and mobility in trees have been recorded (Pulford and Watson, 2003). Lead, chromium and copper are observed to be immobilised and mainly held in the roots favouring the use of willow to phytostabilise these heavy metals. Cadmium, nickel and zinc are more easily translocated to the above ground biomass (Macgregor et al., 1996). Dickinson and Pulford (2005) conclude that the evidence for utilising coppice willow to decontaminate soils note that Cadmium as showing the most promising future particularly when found in slightly elevated concentrations such as in agricultural land that have been subject to high applications of phosphate fertilisers.

A restraint in the potential of willow to remediate contaminated soils is the interclonal variation in the growth of willow in contaminated and uncontaminated soils (Punshon and Dickinson, 1999). Whilst this variation is noted as causing difficulties when undertaking screening programmes, these variations can prove valuable if we are to achieve an appropriate site remediation strategy using willow through selective planting. The ability to selectively plant a site with appropriate willow will only increase given current willow breeding programmes. These breeding programmes could provide opportunities to produce willow clones with characteristics suitable for phytoremediation, particularly metal uptake, tolerance and high biomass production. (Pulford and Watson, 2003).

1.8 Additional Opportunities from Growing Willow Short Rotation Coppice on Disturbed and Contaminated Industrial Sites

Most research to date has concentrated on developing the fine details for the growth of willow SRC on arable land (McElroy and Dawson, 1986; Kopp et al., 2001; Mitchell et al., 1999). The reality of the situation however is that returns from its growth on such land in competition with arable crops or livestock farming has not as yet seen its large scale adoption by the farming community (Walsh and Brown, 1999, Heaton et al.1999, Heaton et al., 2001), as it imposes such high cost penalties on the pioneer growers (Rosenqvist and Dawson, 2005). Some inroads were made initially on set aside land where SRC could be grown to provide an additional income to set aside payments. SRC has also been planted in those areas of the UK where an identifiable outlet for the SRC has been developed e.g. the ARBRE Project in Yorkshire (Hilton, 2001). However a major constraint to its adoption by farmers has been the lack of identifiable markets for the end product. Many of the success stories to date have concentrated upon those projects where an end use has been identified from the outset such as energy, basket weaving etc. Consequently the willow production has developed to serve a demand for the end product.

As an alternative to agricultural land, the potential for utilising disturbed industrial land presents significant opportunities (Rawlinson et al, 2004; Vandenhove et al., 2001; Nixon et al., 2001; Bungart and Huttul, 2001). The economic equation in considering the potential of SRC would however require to be readdressed and considerations would need to be made of additional opportunities which might prevail (Licht et al., 2005; Vandenhove et al., 2002) The financial benefit from the sale of SRC grown on contaminated or derelict sites as a biofuel, source of raw material or whatever financial opportunity that may prevail would also need to be assessed in terms of other sometimes difficult to quantify benefits which would be accrued both locally and at national level. These might include some of the following options.

1.8.1 Site Enhancement & Stabilisation

Improving derelict and contaminated sites appearance benefits not only the site itself but also the whole surrounding vicinity. Such sites can act as a blight upon the surrounding area detracting from any inward investment and the potential economic benefits that this may bring (Duggan, 2005). Whilst planting a site with willow does not represent an immediate remediation of the site it does improve the site’s outward appearance and can be used to reduce any potential leachate and runoff from a site (and thus contamination of adjacent areas) by reducing the through flow of water (Licht and Isebrands, 2005). Being a fast growing tree species will ensure that a site whose appearance has been a blot on the local landscape for generations can be visibly transformed in the course of one or two years to what would appear as a dense ‘woodland’, making a once hostile environment appear green. With the development of the ‘woodland’ a site would be a more attractive location to locate next to, leading potentially to job creation and inward economic gains.

1.8.2 Sewage Sludge Disposal

The cessation of the sea disposal of sewage sludge at the end of 1998, as a consequence of the implementation of the European Urban Waste Water Treatment Directive 1991, (91/271/EEC) there has been placed upon the water companies a need to consider alternative disposal methods for the sewage sludge that they produce.

The United Kingdom is scarred with derelict land, the legacy of our past industrial activities. Reclamation of these sites by the statutory bodies progresses yet the potential to utilise these sites for the disposal of sewage sludge could represent a significant opportunity to both the water authorities and those involved with the remediation of contaminated sites. Sewage sludge can be beneficial to land requiring renewal (Williams and Limbrick, 1995; WRC, 1995, Riddell-Black, 1995). Benefits to contaminated sites include -

- Improvement of the soil structure
- Prevention of erosion
- Improved water holding
- Improved drainage
- Improved root penetration
- Provision of nutrients
- Encouragement of biological activity

Planting those sites amended with sewage sludge with SRC will utilise the nutrients released by the sludge, providing a valuable source of inorganic fertiliser for the willow. In addition an increase in the organic matter content of the soil provides a more amenable growing medium for the willow to survive.

The disposal of sewage sludge and the growth of SRC on contaminated land clearly has combined benefits (Williams and Limbrick, 1995; WRC, 1995). Remediators of contaminated and derelict land have a requirement for organic matter and a source of nutrients to improve the growing medium of a site. This represents an opportunity for those requiring to dispose of sewage sludge and those obligated to remediate contaminated and derelict land. The growing of SRC could be a catalyst to bring together two areas of environmental conflict to produce a renewable form of energy and reduce environmental degradation (Mirck et al 2005).

1.8.3 Carbon Sequestration

The UK government and devolved administrations in consultation with business are implementing a framework, that will draw together in an integrated way a range of instruments and measures to reduce greenhouse gas emissions. These include

- Economic instruments such as the climate change levy, emissions trading, enhanced capital allowances and grant schemes.
- Technology deployment through the ‘Carbon Trust’ whose role is to deliver a support programme to assist businesses prepare for a low carbon future.
- Regulation through the IPPC (Integrated Pollution Prevention and Control regulations) requiring the use of best available techniques, and through reviewing efficiency provisions in the Building Regulations for England and Wales and the Building Standards (Scotland) Regulations.
- Measures to make the market work better
- Improving public and company information

One such instrument is the greenhouse gas emissions trading scheme. UK–based projects designed to deliver emission reductions can generate credits which can be sold into the emission allowance market. As a minimum, project managers need to be able to demonstrate that the emission reductions are additional to a ‘business as usual’ baseline. Before any credits are awarded, the projects must go through a stringent monitoring and verification process. In due course, it is envisaged that these emissions will be tradable on international markets established under the Kyoto Protocol.

In the DTLR A Greenhouse Gas Emissions Trading Scheme for the United Kingdom – Consultation Document (DTLR, 2000) the following government views were expressed-

“6.8 The Government remains convinced that the UK’s priority should be emission reductions rather than carbon sequestration because of the complexities and uncertainties involved with forestry projects and other carbon sinks. For the time being, the Government believes that sequestration projects should not be eligible under the UK trading scheme. However, the Government does recognise that forestry projects can provide environmental benefits and it will be keeping this issue under review.”

Discussions on the rules for the Kyoto mechanisms in The Hague in 2000 were initially held up by the inability of concerned parties to reach agreements on the use of carbon sinks. Interestingly from the point of view of carbon sinks, the stumbling block in this meeting had been the failure of the French minister (according to the UK Deputy Prime Minister) to understand the proposals that the United States Government were aiming to include. One of these proposals by the USA sought to use their vast forests as sinks for the greenhouse gases released in the USA.

Clearly the potential to use SRC plantations as a carbon sink represents an opportunity to be explored. Andersen et al (2005) note the potential of SRC to displace 6 Mt C from fuel oil in Scotland alone. At present financial benefits from planting SRC as a carbon sink are limited although positive PR from such an exercise e.g. a car manufacturing company planting SRC to offset the expected CO_2 produced from their vehicles over their life time may have some benefit in promoting their vehicles as carbon neutral.

1.8.4 Amenity and Wildlife Havens

Woodlands are today viewed with increasing interest in terms of their amenity value and even the social and welfare benefits that they bring to those communities that utilise these areas (Dennington et al., 1982). The location of the field trial used in this study is itself an example of this where a once hostile inhospitable site adjacent to a new housing development attracts dog walkers, children and families who are encouraged to make use of the pathway network implemented on the site. A once hostile environment represents an important habitat in an otherwise urban setting. The benefits of willow short rotation coppice to wildlife have also been demonstrated in studies undertaken (Sage et al., 1994, Sage and Tucker, 1997). Results of their studies have indicated that willows provide a valuable habitat for invertebrate species in comparison to other trees and dependent upon the nature of the ground cover under willow can provide a valuable habitat for game birds.

1.8.5 Reduced Management Costs

Utilising derelict and contaminated (even vacant) sites for the production of willow SRC may have potential benefits in terms of savings to the management costs of these areas when compared to say their upkeep as grassed areas. Work undertaken by the former Scottish Development Agency (the forerunner to what is today Scottish Enterprise) noted the expense of maintaining many reclaimed sites (Pers. Comm Duncan, 2005). Little thought was given to the ongoing maintenance costs for the land reclamation projects undertaken by the organisation. In some of these projects willow SRC would have provided a more cost effective alternative to the management of these sites as opposed maintained grassland requiring regular inputs to cut the grass sword. (Pers. Comm. Duncan, 2005).

1.9 Conditions Required For the Successful Establishment and Growth of Willow Short Rotation Coppice

Guidance issued (DTI, 1994, ADAS, 1995, Mitchell, 1995, DTI, 1996, Forestry Commission, 2002) point to the following requirements to ensure maximum yield from SRC on conventional agricultural land.

1.9.1 Site Selection and Preparation

Sites at an elevation greater than 100m above sea level will demonstrate a reduction in yield due to a decrease in the number of growth days and as a result of exposure to the climatic elements. Willow is considered as suitable for growing on a variety of soil types ranging from mineral to organic soils, although soils with greater than 25% organic matter may pose problems in terms of the difficulty of weed control and potentially nutrient availability and pH.

Ideally soil depths should be no less than 30cm with a pH value suited for growing willow, not higher than 5.5. If rabbits, hares or deer are present then stock proof fencing should be a requirement to ensure against damage to the young crop. Prior to planting the site should be rotavated or ploughed followed by a disc or harrow to prepare a fine tilth into which the willow cuttings can be planted.

1.9.2 Planting

Cuttings can either be planted by hand or utilising some of the conventional planters like the cabbage planter or the newer specialist planters which are now available for purchase or hire. These are able to plant not only individual cuttings but also full-length willow stems – ‘rods’, can be cut into lengths and planted into the ground in one operation utilising such equipment as the *salix* maskiner planter developed in Sweden

Planting densities of 10,000 stools/ ha and greater have been known to be established these are usually planted in double rows at distances of 0.9m between plants, 0.75m between rows of plants and 1.50m between these rows to allow vehicle access. It is also usual practice to stagger planting to allow more space for each individual tree to grow and to assist the mechanical harvest of trees as it enables each stool to be fed into the harvester sequentially. Proe et al., (2002) considered the effect of increasing planting densities on willow yield. A notable result of their research was that whilst over time yields were comparable for differing planting densities, wider spacing and early coppicing required additional weed control. Research by Bergkvist and Ledin (1997) also noted that initial yields were higher for willow planted at higher densities, however, over time these reduced. Stand closure was again viewed as an important factor in the planting design, with recommendations for willow plantation design at lower densities without losing yield potential.

Figure 1.3 Mechanised Willow Planting Operation

Selection of the willow cultivars or clones requires careful consideration to ensure maximum yields for the relevant site conditions and to avoid the spread of disease, in particular rust the primary pathogen being *Melampsora* *(*McCracken & Dawson, 1992, McCracken et al., 1996*)*, a disease that can cause early leaf fall and can be succeeded by secondary pathogens causing stem dieback and crop failure. The clones planted must be of mixed parentage with monoculture crops being avoided. So severe can the initial effect of rust be that up to 60 % stool death has been recorded at spring flushing by Dawson & McCraken (1994). Whilst fungicides are available to control rust disease, McCracken (1997) has estimated that this would need to be applied up to 16 times at fortnightly intervals during the growing season to be effective, clearly an impracticable and unviable option.

A simpler and more effective practice has been to avoid monoclonal plantations at all costs. Indeed parental diversity is strongly recommended in the planting mix to avoid susceptibility to particular pathotypes of rust as the response of different clones is known to vary (McCracken, 1997). For this reason it is recommended that no more than two rows of the same clone are planted adjacent to each other. Should the crop then become infected by rust the rate of spread is reduced as clones of different parents are known to exhibit differing susceptibility to the pathotypes of rust that exist.

Clone selection has also been advocated by Wiltshire et al. (1997) in the control of willow-feeding leaf beetles (*Coleoptera & Chrysomelidae)* another favoured pest of willow. However in contrast to parentage to control rust it was the concentration of leaf phenolic glucoside that deterred feeding on the willows by the willow beetles, with individual clones such as *S. eriocephala*, *S. purpurea* and *S. burjatica* being singled out for use as effective in a plant breeding for resistance programme.

1.9.3 Weed control

Rust and willow beetle apart, competition from weeds and the need for an effective management programme to control weeds represent a significant input into the establishment of a SRC crop. For the effective establishment of SRC on arable and grassland sites the applications of herbicide e.g. glyphosate are advised pre-planting to eradicate perennial weeds followed by post-planting residual herbicides e.g. simazine to ensure the long-term control of annual weeds. In addition further applications of foliar-acting herbicides to kill late emergent weeds may be required during the growing season. As willows are susceptible to some of the chemical weed controls careful selection of herbicide will be required to address not only the type of weeds prevalent but also to ensure that the willows are not damaged, in some instants this has been undertaken mechanically using ‘finger-weeders’ or where the plot is small enough a mechanical garden rotavator.

Figure 1.4 Agricultural Sprayer Adapted to Prevent Damage to the Willow SRC Crop

Full weed control is advised until canopy closure is sufficient to avoid competition from competing weeds. This action may have to be repeated following the first coppicing of the willow. The importance of effective weed control in plantations can result in variations in the growth of willow (Tahvanainen and Rytkonen, 1999). This is again observed by Rawlinson et al. (2004) who notes that weed competition can have the largest inhibitory effect on establishment of trees on former landfill sites. Forestry Commission guidelines (Willoughby and Clay, 1996) provide valuable assistance in countering this issue providing advice on suitable herbicides for appropriate conditions.

1.9.4 Fertilisation and Irrigation

Compared to other arable crops it is noted that willow is less demanding when it comes to fertiliser with estimates of one fifth being quoted by Macpherson (1995) compared to cereal crops. Mitchell et al., (1999) note that the need for fertiliser will depend on the initial nutrient status of the growing medium. Trials undertaken on arable land (Mitchell et al., 1995) note no significant increase in yield through fertilisation in the first ten years of crop management. In general it has been observed that on most arable sites fertilisation is not required (Dawson, 1988) as harvesting occurs after leaf fall ensuring that some of the nutrients are recycled, indeed the application of fertiliser may be deemed as non-beneficial by reducing yields due to increased competition from weeds. On less fertile sites the application of fertiliser may be beneficial (Mitchell et al., 1999) or provide short term gains (Mead, 2005).

The high demand of willow for water is well known being a well-established feature alongside UK rivers. In some mainland Europe countries the planting of willow necessitates irrigation, and in sandy soils the requirement for irrigation is often viewed as a limitation on the use of a site for establishing SRC (Vandenhove et al., 2001). Fortunately at present this is not to great an issue in the UK.

1.9.5 Harvesting

Harvesting can occur any time 2-5 years after the initial coppicing usually after the trees have senesced. This can be undertaken mechanically, utilising an adapted forage harvester to undertake direct chipping or utilising some of the specialist equipment now available which produce bundles of cut stems, suitable for drying at the field edge.

The mechanics for growing willow is a well researched field when its growth is considered on arable land (McCracken et al., 2001; ETSU, 1993, MacPherson 1995) Given the area of contaminated sites available for its growth in the UK alone and the additional benefits that may be derived from planting up such sites with willow SRC, there is a need to examine and quantify this potential. The overall aim of this work is to consider the methods best suited to the production of willow SRC on industrially contaminated and degraded sites and to address the potential benefits that may be provided from its establishment.

Figure 1.5 Willow SRC Being Harvested

1.10 An Evaluation of the Potential End-Uses for Willow Short Rotation Coppice

1.10.1 Introduction

In 2002, a blow was dealt to the UK biomass industry with the announcement that ARBRE Energy Limited owned by First Renewables Limited was to be put into liquidation. The purchase of First Renewables Limited from the Kelda Group Plc in 2002 included in its sale an agreement from the Kelda Group to provide ongoing development funding for the project until the plant was able to demonstrate economic viability. One of a number of reasons that financial support for the project could be discontinued by Kelda included the ability to withdraw if in their opinion the project would not be technically or economically feasible. In July 2002 this support ceased with the consequence that the ARBRE Energy was unable to meet the demands of its creditors and was technically insolvent.

This first prototype plant in the UK was designed and constructed to prove the technology of wood gasification in relation to power generation. Its primary source of fuel was derived from crops of short rotation coppice grown on arable land in the vicinity of the plant at Eggborough near Selby, Yorkshire (Hilton, 2001). The importance of this project to the UK government in meeting its international obligations to reduce greenhouse gasses cannot be underestimated. Its importance and potential to assist in the diversification of rural economies, through the provision of an opportunity to grow new crops, create local employment and in terms of international trade (with the technology being easily adaptable to other sustainable energy sources such as rice husk, sugar cane waste) through the export of plant and professionals who have developed this technology was considerable.

Whilst the ARBRE project failed optimism in the industry continued. In a statement issued by Brian Wilson, Minister at the Department of Environment, Food and Regional Affairs following the failure of the ARBRE project he stated that :

"I regret the failure of any project , particularly when it is accompanied by job losses. However, I remain hopeful that this plant can be brought into full commercial operation under a different owner"

Indeed the Government included in their statement a call to encourage any developer wishing to carry on the work at ARBRE to come forward. This never happened and the plant and equipment was eventually relocated to Asia.

The collapse of this project at the forefront of the UK biomass energy programme, whilst being a significant blow to the aspirations of the industry, should not be viewed as a complete end of any proposals to utilise biomass energy in the UK. Indeed the ARBRE project in itself developed much experience in clone selection, SRC crop management, supply control in addition to the experience developed on the technical operation of the plant (Hilton, 2001). Bioenergy represents one of many potential outlets for SRC. Whilst being credited as being one with great potential it is by no means the only end use.

The interest of the UK government in supporting biomass since the demise of the ARBRE project has seen £66 million provided in capital grants for biomass projects in addition the Renewables Obligation being imposed upon energy suppliers requires them to obtain 15% of their electricity from renewable sources, including biomass by 2015. In 2004 a new £3.5 million UK Wide Bio Energy Infrastructure Scheme was introduced to help harvest, store, process and supply biomass for energy production. A task force was established to undertake a one year study of biomass to consider its potential in combating climate change, boosting farm diversification and creating rural jobs whilst looking at the barriers needing to be overcome to establish confidence in the industry.

In 2004 the Royal Commission on Environmental Pollution published a special report on biomass (RCEP, 2004). The report noted that biomass has the potential to provide a significant contribution to the reduction of carbon dioxide levels if substituted for fossil fuel in the generation of heat and electricity. Biomass it notes has the potential to help significantly towards meeting renewables targets in the electricity supply and make an important contribution in the generation of renewable heat and combined heat and power.

1.10.2 Existing and Potential End Uses for Willow SRC Biomass

The traditional image of willow *(Salix)* has been that of cricket bats *(Salix alba caerulea)* and basket weaving *(Salix viminalis)*, whilst these industries and varieties still exist the current interest is in those high yielding clones grown for their biomass i.e. their ability to produce relatively large volumes of wood biomass over a relatively short period of time (Larsson,1998). Their ability to be coppiced is also an important aspect of willow, that is their ability to be cut to ground level to stimulate increased growth and stem number. Rotation length of willow can be adjusted to suit the local conditions and influence the biomass yielded by the SRC (Mead, 2005; Proe et al., 2002; Armstrong and Johns, 1997). These factors combined with its suitability for growth in Western Europe make willow SRC an attractive biomass crop.

The growth of willow as a biomass crop is slowly becoming a recognised commodity, however the need to identify outlets and uses (Ledin, 1996) for the large volumes of wood biomass capable of being produced are only slowly being addressed.

Within the context of this thesis current and potential end uses for willow will be considered in two categories,

- Energy related uses
- Non - energy related activities.

1.10.3 Energy Related uses - Bioenergy

Properly managed biomass resources are renewable and sustainable and may be considered as carbon neutral (although this does not include the energy used in planting, harvesting etc.). Burning biomass rather than fossil fuels, like coal or diesel can reduce emissions of the gases responsible for acid rain, as well as cutting fossil emissions of carbon dioxide (CO_2), the main gas responsible for global climate change.

Bioenergy addresses many of the key issues and problems surrounding sustainable development, including combating global climate change, supporting and creating jobs, strengthening rural economies, enhancing the rural environment and recycling resources. Bioenergy developments create new employment opportunities in manufacturing, construction, plant operation and servicing and in fuel supply.

Sweden have developed an advanced energy-crop development programme, in response to the oil energy crisis of the 1970’s (Duggan, 2005) with extensive breeding achieving ever-increasing yields and improved pest and disease resistance (Larsson,1998). Ongoing development of planting and harvesting equipment and best practice for crop establishment, management and harvesting are all part of this extensive programme.

The transition from fossil carbon fuels will be evolutionary rather than revolutionary. This is the great strength of bioenergy, an opportunity to move towards a sustainable energy economy while maintaining and improving quality of life. The energy potential of willow biomass is probably the more obvious of end – uses which we can associate with willow (Patterson, 1994), however the way this is realised by direct combustion or by initial upgrading into more valuable and useful fuels requires consideration (ETSU,1995' ETSU 1999)). Figure 1.2 shows many of the pathways available.

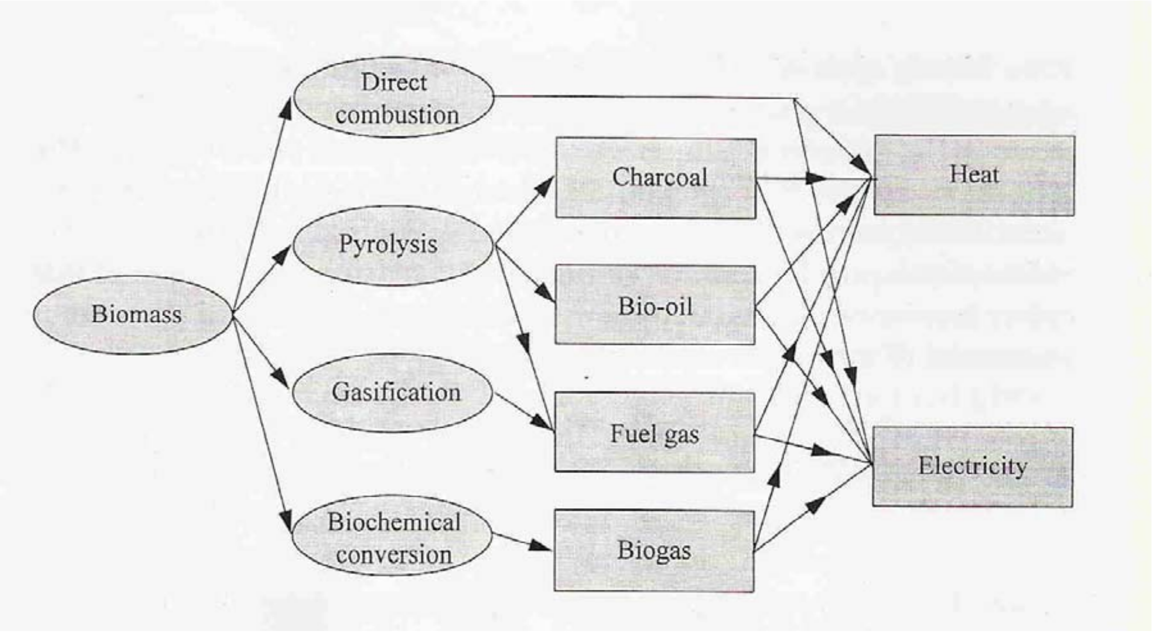


Figure 1.6 Energy Conversion technologies for heat and electricity production from biomass fuels (Nordin & Kjellström, 1996)

(i) Direct Combustion

Probably the most well known and widely practised form of use that we would associate with the use of wood, combustion implies the complete oxidation of the fuel to water and carbon dioxide with the release of heat. Whilst direct combustion as a percentage of total energy used in the western world has diminished considerably in developing countries wood remains important for both cooking and heating. In Western Europe modern convenience living together with strict air quality controls in most urban environments has seen the decline of wood burning in the home, however in the rural setting wood still has an important role to play (Nordin & Kjellström, 1996). Development of more efficient combustion equipment which reduce emissions and increase overall energy efficiency are the subject of ongoing research (Cowburn et al, 1997). Several varieties of units are now available on the market which have greater conversion efficiency and limit discharge of polluting emissions. Figure 1.3 illustrates some of the small scale combustion units that are available on the market. These units are designed to maximise wood burning efficiency and reduce discharge of emissions through greater control of the combustion process, however these in themselves are unlikely to see the large scale return to biomass use in the home.

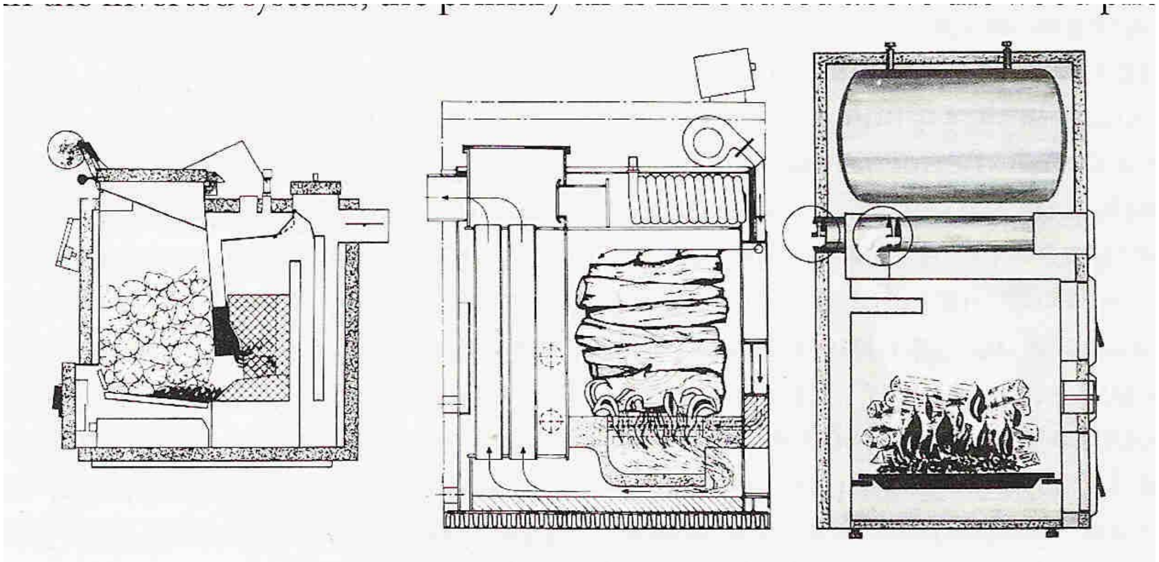


Figure 1.7 Illustrations of the commonly used small scale combustion units. (Nordin & Kjellström, 1996)

Moving away from a domestic level to an industrial scale the combustion of wood biomass to provide electrical power continues to have relevance particularly in those countries with a large wood resource e.g. Sweden and the United States. Despite the existence of a few wood combustion plants across the world, interest in wood for electrical generation via a simple steam cycle used in a normal thermal power station is moving in the direction of gasification due to greater efficiency.

(ii) Gasification

This process for utilising willow biomass as a fuel involves its conversion in the first instance into a combustible gas (Bridgewater, 1995). This is achieved via a partial combustion process i.e. in the presence of a limited supply of air/oxygen. The products of this reaction consist of carbon monoxide, hydrogen and methane as the main combustible components, the balance consisting of carbon dioxide, water and nitrogen (Nordin & Kjellström, 1996). The gas produced can be used as a fuel in a number of applications where the solid biomass fuel can only be used with difficulty, for example -

- fuel for oil fired furnaces
- Operation of engines (gas turbines etc)
- The direct drying of agricultural products

The gasification conversion technologies, as they are many and varied (Figure 1.8), are very much dependent on the end use of the gas fuel produced.

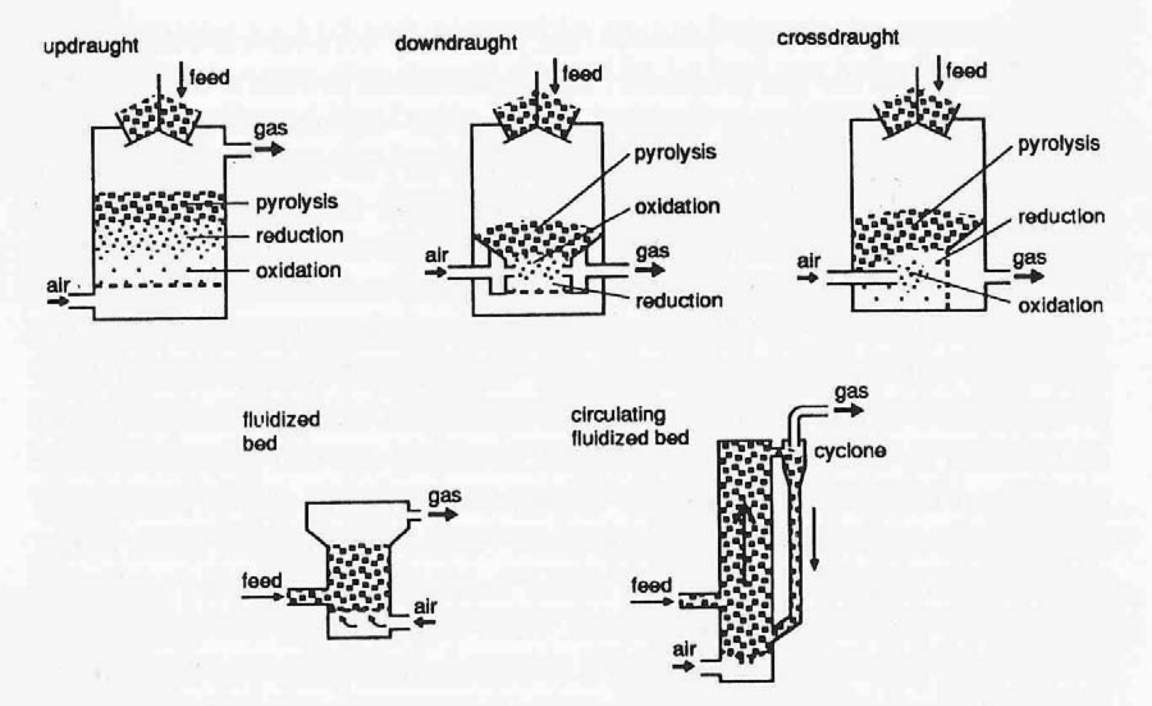


Figure 1.8 Units for the gasification of wood biomass (Nordin & Kjellström, 1996)

In the UK the ARBRE project at Eggborough, North Yorkshire was an example of wood gasification which aimed to produce approximately 8Mw of electricity, enough to supply approximately 18,000 people. Smaller projects such as at the Enniskillen College and Brook Hall Estate (100Kwe) are also well-documented examples, providing both heat and electrical energy. (ETSU, 1998)

(iii) Pyrolysis

Pyrolysis is a process for the thermal conversion of solid fuels in the complete absence of air/oxygen, or with such limited supply that gasification does not occur to any appreciable extent (Nordin & Kjellström, 1996). The end products from this process are charcoal and, or the production of a liquid product bio-oil. Charcoal currently has a market for certain industrial processes and as a smokeless fuel e.g. barbecues. Current use for bio-oil is as a feedstock for extraction of a food additive ‘liquid smoke’, however the potential as a substitute for fuel oil and as a feedstock for the production of synthetic petrol or diesel fuel does represent some opportunity. As with gasification the end product from pyrolysis is very much dependent upon the reaction route taking place i.e. slow pyrolysis at low temperatures between 400-800 degrees centigrade gives a high yield but also produces a high volatile content, changing the conditions of the reaction gives different results which can affect the viability of the operation, all issues will need to be considered (Nordin & Kjellström, 1996).

Bio-oil engines have been developed which are able to run on this liquid fuel, it is also possible that the bio-oil could be used for the extraction of other specialist chemicals, or the residual oil remaining after valuable chemicals have been removed can find a substitution for chemical products. Its use as a boiler fuel has been successfully tested, however the acidic and corrosive nature of the oil leads to additional cost in the boiler system design. Viscosity is also a problem for bio-oil as during storage this tends to increase requiring a fast turnover in its use. Pyrolysis represents an area of much interest however the answers and solutions to the problems which it entails are not yet apparent.

(iv) District Heating

The use of wood as a fuel to provide district heating i.e. heating and hot water to an entire community via 1 central boiler as opposed to individual boilers in each home represents another opportunity for utilising willow SRC as a fuel source. A joint venture by the company General Des Eaux, the French Water Group and Border Biofuel hopes to see the establishment of a wet central heating system in terraced and semi-detached houses in the North of England. In return for a fixed term contract free installation of the heating system is offered or connection to the existing system where one already exists, customers will be charged via a heat meter. In this project the central boiler will initially be fuelled with forest residues, as Dr. Adrian Bowles formerly of Border Biofuels noted that SRC was not acceptable to the financiers of the project as there was insufficient SRC biomass in existence (Pers Comm Bowles,2001).

A similar project at the Shenstone Lodge School in Staffordshire utilises wood biomass to provide heating and hot water to a school and dormitories via a 150kw boiler. The System was delivered to the school as a complete unit in a container and linked to the existing system. Woodchips are delivered once a week and fed into the boiler automatically. This project is currently a research project funded by the Energy Technology Support Unit and the boiler manufacturers, its performance is being continuously monitored (West Wales Task Force, 1996).

(v) Fuel Cells

Fuel cells produce electricity without emitting any gases, they function in a similar manner to a battery apart from the fact that they cannot store energy and is not sealed, thus it can be constantly fuelled. The end product from the fuel cell is a constant flow of electricity, with the useful by-product of high quality heat. Gas produced from biomass gasification could be successfully used as a fuel in such a cell, although there are no well known examples of such a project at present (ETSU, 1998).

(vi) Non-Thermal Conversion Processes

The main player in this field is the biological conversion of biomass to produce either heat or combustible gas (methane being the main combustible component) through the fermentation of carbohydrates derived from plant material. Conversion can be undertaken in the presence of oxygen (aerobic decomposition) or without (anaerobic digestion). Aerobic decomposition has traditionally been a treatment process for animal waste to produce fertiliser, however of interest in the anaerobic process is that the biogas produced may be used for energy generation as well as for ethanol production. Anaerobic digestion systems are fairly common in rural India where they are used to provide biogas for domestic uses. The system is not a continuous reaction with 2 or more digesters being required out of phase to achieve constant production (Nordin & Kjellström, 1996).

Much interest was seen in biogas technology in the 70's during the oil crisis. Interest in biogas production has also focussed on its generation from sugar and starch feedstocks (Batchelor et al, 1996). Cellulose from trees is a potential feedstock but at present further research is required before the technology for use of such feedstock is made possible.

(vii) Combined heat and Power (CHP)

Combined heat and power plants represent a co-generation process whereby the waste product from electricity generation, heat, is reutilised for heating and hot water (District heating). The benefit of such systems is that energy efficiency is in the 80-90% range compared to on average less than 40% in a traditional thermal power plant. Very few large-scale projects are in operation, although smaller units have been installed and operated successfully (Nordin & Kjellström, 1996).

CHP technology has for decades not been looked upon favourably in the UK, whereas in Northern European countries it is very much the norm to see entire cities receive their power and heat from a few CHP plants e.g. Helsinki, Finland. In the UK CHP was viewed as being an area of significant interest in terms of increasing energy efficiency (albeit from conventional energy sources). After a successful year in 2000 when approximately 844Mwe of capacity was installed this declined to 38Mwe in 2001(HMSO, 2002). Whilst the % of CHP achieved from biomass is at present negligible when compared to the conventional energy sources it is indeed an area of growing interest providing added value to what otherwise would be waste heat being vented to the atmosphere.

For CHP to be successful in the UK requires a major stumbling block to be surmounted. Whilst large scale heating plants might be the norm in many Northern European countries, the UK still exhibits a tendency where each individual household and individual premise all have their own private heating systems. The concept of heat and hot water being provided to an entire city from one central plant is alien to the UK (with the notable exception of the City of Sheffield which has a long established district heating scheme). With the exception of practitioners in this field it is a concept that the majority of the UK population seem unable to grasp, although inroads are being made with small local heat loops providing heat and hot water to small user groups e.g. Whitehall Government Offices in Westminster, London.

Examples of small scale real biomass heating and CHP in the UK include Weobley in Herefordshire, Brook Hall Northern Ireland, which sells electricity to the local electricity grid and provides heating for the large house and the Ecotech rural business centre in East Anglia. Biomass heating is now to be used in several of the most innovative building projects of our day, including the greenhouse of the Welsh National Botanic Gardens designed by Norman Foster, the Eden project in Cornwall, The Earth Centre and the new Heart of the National Forest Centre. While 'mini power stations' supplying electricity to the grid will play an important role, of equal, perhaps greater, importance is the opportunity to apply biomass heating and CHP at the small, local scale in homes, businesses, schools, hospitals, leisure centres, rural factories and so on. In contrast to the small scale operations in the UK a demonstration CHP station in Varnamo in Sweden produces 6Mwe and 9Mw heat for 600 households from 4-6000ha of willow SRC. (ETSU, 1997)

(viii) Densified Fuels/ Briquetting/ Pellets

The end use for this product is energy production, however it deserves a mention here as the process is important in reducing transportation costs per energy unit. Reducing the transportation costs of wood shavings, sawdust and dry chips from wood for example, by the production of briquettes, allow the waste product to be considered as a replacement to oil in say a boiler system. In Sweden pellets are a commercial reality with the upgraded wood fuels being shipped from the north to large pulverised fuel-fired plants in Stockholm. Not only can these pellets be used in large power plants, but supply logistics and automated boiler technology are at such levels in Sweden and Austria to allow individual houses to be supplied with pellets for use in automated house boilers in a similar manner to gas and oil boilers in the UK at present. The level of automation is greatly removed from our conventional image of wood biomass having to be cut, transported and handled several times over before it is finally placed in a dirty and inefficient open fire or log burning stove (Nordin & Kjellström, 1996).

Co-combustion with fossil fuels is also an argument in favour of densified fuels as –

- The modifications required will be limited
- Seasonal fluctuations in biomass production can be compensated by the fuel mixture
- Higher costs for biomass in some cases can be economically compensated for if only a fraction of coal is substituted
- Sulphur and Nitrogen Oxide emissions are reduced by the introduction of biomass fuels.

An EU research project has focussed upon the area of co-combustion called the BAGIT Project – Biomass and Gas Integrated CHP Technology, however questions regarding the sustainability of re-circulating the ashes produced from the system have necessitated further research as recycling is a requirement for the sustainable use of biomass (BAGIT, 2003).

(ix) Green Electricity

The potential sale of electricity derived from a renewable source for a premium price is at present stimulating much interest. Dutch and Danish experience with consumers has seen a very favourable response with more consumers than anticipated being prepared to pay what some commentators have referred to as a voluntary tax. In the UK the jury is still out on this issue, however NETA (The New Electricity Trading Agreement) did place a renewable obligation (RO) upon electricity suppliers to purchase a percentage of their electricity from renewable sources, with those suppliers already supplying greater than recommended percentage being allowed to trade their surplus renewable certificates.

1.10.4. Non-Energy Related Activities

Most current willow biomass uses relate to its potential for energy generation and many activities are concentrated within this field. Whilst a few activities do occur out with this scope, it is important to note that many are inter-related.

(i) Biomass Refining

Advanced trials in Canterbury, New Zealand by Scott Covertech Ltd are producing a range of fuels and chemicals from biomass. This is achieved by the washing out of alkaline salts in the biomass that inhibit burning efficiency. The result of this is the breakdown of the biomass into its chemical constituents such as sugars, cellulose, lignin and volatiles. Further drying of this output produces a product called cellulig which is used in power generation. The washing process itself provides for nutrient removal which is a potential useful fertiliser (Nordin & Kjellström, 1996).

(ii) Feedstock for the Forest Product Industry

SRC willow crops represent a potentially valuable source of fibre which can be used as a supplement to, or as a direct substitute for wood in the manufacture of forest products e.g. particleboard (chipboard), medium density fibreboard (MDF) or pulp for paper. Insufficient knowledge and understanding of the production costs and product properties have seen MAFF fund several projects to identify the most promising alternatives to timber (Hague, 1997). The results of these projects seemed to suggest SRC as having a potential as a feedstock for MDF production although in this instance it should be noted that the SRC used was derived from poplar and not willow.

(iii) Other varied and miscellaneous uses

The use of SRC to provide mulches for playgrounds or in land reclamation projects is an area of use open to further exploration. Other sometimes bizarre end uses have included coffin production, bund construction and erosion prevention for riverbanks. These are viewed as having a limited market only.

The main use for willow SRC is at present focused towards an energy end use, and where non-energy uses are dominant there is often an overlap. This has already been noted for refining, but the same can also be said to be true for MDF and chipboard plants in some countries where the heat energy requirement for the manufacturing process and electricity generation proceed side by side. Limitations to further development of SRC as a feedstock for the forest product industry are compounded by insufficient data on product properties.

Across the whole willow biomass end use industry it would seem that supply problems are an instrumental stumbling block in the establishment of end uses, with the lack of supply affecting end use, and vice versa (Gigler et al., 1999).

At present it would appear that for the supply or end use to be successful, both will require to be developed in conjunction with each other. Various levels of research projects are being undertaken, however full-scale commercial operations utilising willow SRC in the UK are only cautiously emerging.

(iv) Combined Projects

Whilst individual potential end-uses of willow have been identified above it is important to consider the combined benefits that growing willow SRC can bring to a project as has already been noted. The production of willow SRC on its own may not always provide the economies that are required for its successful commercial production. Combine its production with other factors providing solutions to both local and national issues and a potentially unfeasible project could become more attractive. An example of this might be in a land restoration project.

In a recent project in Glasgow, willow biomass was considered as part of the solution to the restoration of a former landfill site.

As part of an enhanced restoration scheme for a Landfill Site, the landfill operator wished to consider the potential for utilising part of this site for the production of energy from biomass/ wood waste arisings. The main source of fuel would be derived from

- wood removed from the waste stream at a newly constructed waste recycling facility.
- biomass produced on the landfill site itself, both forest residues and short rotation willow coppice.
- biomass waste produced by the local authority estimated to be in the region of 50,000 tonnes per annum, currently disposed of either to landfill or by burning in large open air pyres.

The electrical energy produced would be used on site. Opportunities to sell this electrical energy into the national grid would be considered as there was already in existence on the site gas generators producing renewable energy from the methane gas released and collected from the landfill site. These generated electricity as part of a SRO (Scottish Renewables Order) with a set price per kWh being guaranteed over the life span of the SRO. The SRO scheme has now ceased to give out new contracts however a new trading agreement – the New Electricity Trading Agreement (NETA) is intended to encourage those companies that supply electricity to purchase 15% of their supply from renewable sources, consequently there might be scope to sell the electricity produced to an electrical supplier.

Whilst there are no limitations on the size of energy plants that could be built to operate on wood or biomass, constraints will often be imposed by the availability of fuel. This will either limit the operation of a plant or if taken into consideration at the design stage, ensure that the plant size is suited to the available supplies of fuel.

In the project under consideration for Glasgow, as no indication of the level of wood fuel supply was available at this site so as to calculate the scale of power plant that could be sustained in this project, the internal energy requirement of 500kW on the site itself was utilised as a starting point.

As a rough indication of costs for a wood fuelled combustion energy plant, each kW of installed electrical capacity (utilising conventional combustion technology) would cost in the region of £2000/ kW (Talbott, 2001 Pers Comm). Consequently the internal requirement of 500kW at this site would require a plant costing in the region of £1million requiring between 16-24 tonnes of wood fuel a day to provide this output (5840 – 8760 tonnes per annum). Table 1.4 provides the breakdown of costs for a Combined Heat & Power System Rated at 500kWe. Table 1.5 shows the basic output values for combined heat and power units, their costs and feed rates.

Table 1.4 Breakdown of costs for a Combined Heat & Power System Rated at 500kWe (Talbott, 2001 Pers Comm)

Type	Outputs Electrical=e Heat=T	Silo	Combuster	Steam Boiler	Electrical Turbine & Pipework with controls	Flue	CO & O_2 Monitor Temperature, Particulate	Delivery, Ins Commissioning
CHP 500	500 kWe 3000 kWT	$200m^3$ £110k	C25 G.W.B. £348,750	£189,000	£316,518	16m £25,000	£22,500	£50k Total £1,061,768

Efficiencies from the production of electrical energy alone are known to be very low. Irrespective of which technology is used to produce electrical energy, an engine or generator will only convert approximately 16% of the energy into electricity (the remainder being emitted as heat). An unit currently being developed by one supplier with a rating of 50kW electrical has a 45% efficiency (which is considered high!). This utilises super heated air to turn turbines, not steam. If the waste heat can be recovered and used effectively such as in a combined-heat-and-power (CHP) system the total efficiency can be increased to 85% or more and potentially allow a further income stream to be generated.

In this project there were considered limited opportunities to utilise heat on this site in the offices, however there may be some scope to sell the heat component (through a district heating system) to new housing developments being planned on adjacent land, however this option remains to be explored.

The cost of grid connection is considered as being site specific and will depend on proximity to existing grid lines/ transformers and on their ability to receive the generating capacity without any upgrades. A 500 kW output however is considered as being very compatible with most existing systems being neither to large to require expensive upgrading of existing systems or too small that connection to the grid would be uneconomic to provide sufficient return.

Where “clean” non-treated wood is utilised in a generating plant the limits for the flue gas emissions are set at 150 mg/ m^3, when treated woods are used the waste incineration directive imposes a much stricter limit of 10 mg/m^3 and the requirement for a flue gas cleaning filter. On a positive note this does allow the generating plant to burn waste wood, paper, cardboard and plastics, but adds to the capital costs of the plant by 20-30%.

The main stack emissions from a wood fired plant burning “clean” non-treated wood from forests or SRC will consist largely of water vapour and CO_2 (plus nitrogen and oxygen from the combustion air). The emissions will also contain traces of carbon monoxide (CO), oxides of nitrogen (NO_x), particulates (small particles of dust) and volatile organic compounds (VOC's). These emissions will normally be controlled by

- Operating the plant correctly and efficiently
- Installing pollution control equipment where this proves necessary
- Ensuring proper training for all staff involved in emissions control

SEPA or for smaller plant, the local authority will specify the stack emissions for a particular plant in order to meet UK and European standards.

Waste derived wood used in a wood fuelled generating station is exempt from the climate change levy (SI 2001 838 Climate Change Levy 2001). This ensures that a climate change levy of up to 0.43p/ kWh is not imposed on an unit of electricity produced. Any electricity generated if sold into the grid might also benefit from the renewable obligation placed upon electricity suppliers to secure a percentage of their supplies from renewable sources.

Table 1.5 Basic Values for Combined Heat and Power Units Outputs/ Costs/ Feed Rates etc (Talbott, 2001 Pers Comm)

Unit Size [1]	Unit Cost [2]	Electrical Output ~~[3]~~	Thermal Output[4]	Wood Feed Rate [5]	Maintenance/ Downtime
50 kW (10 Houses)	£250k	50 kW	250 kW (8)	120 kg/ hour (2.88)	30 minutes – 2 hours
100 kW (20 Houses)	£350k	100 kW	500 kW (16)	180 kg/ hour (4.32)	30 minutes – 2 hours
250kW (50 Houses)	£600k	250kW	1000 kW (33)	400-500 kg/ hour (12)	30 minutes – 2 hours
1000kW (200 Houses)	£1.2m	1mW	4000 kW (133)	1.5 tonnes/ hour (36)	30 minutes – 2 hours

Notes

[1] Figure in brackets indicates the number of houses served given a base load requirement of 5kw. (The thermal requirement of a 3-4 bedromed house is assumed to be 25kW based upon a domestic boiler rating of 60-80 Btu.)

[2] Costs indicated are intended as a ball park figure and include such items as the fuel bunker, conversion unit, generating unit and flue, but not the pipe work for a heat distribution network. These costs are for biomass woodchip. If the form or nature of the wood fuel changes such as pellets or refuse derived wood the combustion unit may require to be reconfigured to the correct residence time for clean combustion.

[3] Electrical Output efficiencies are approximately 10%, the addition of the thermal output substantially increases this value.

[4] Figures in brackets indicate the number of houses that could be heated by the thermal output.

[5] Figures in brackets indicate the daily feed rate in tonnes.

As already noted the estimated fuel supply of this plant would be in the region of 5840-8760 tonnes per annum based solely on generating output of 500kW. No estimation has been currently made available of the potential wood supplies both from wood removed from the waste stream or of biomass available from the local authority, however if there were deemed to be insufficient supplies the potential exists to model the site restoration along the lines of an energy park with energy plantations of willow SRC being at the forefront of design considerations as opposed to amenity woodlands. One hectare of well managed willow SRC woodland can be assumed to yield between 9-12 tonnes per year of dry matter (greater with selective clone use and on the higher grades of agricultural lands), consequently if such an option was to be considered for this project alone would require 250-290 ha of land to be planted with willow SRC.

At present this project only exists on the drawing board. The installation cost in excess of £1,000,000 should not in itself be insurmountable with European Grants and UK. funding sources potentially providing 40-50% of the project cost (some requiring payback). The potential to use Landfill Tax Credits might also prevail if the plant utilises material that would otherwise go to landfill.

In August 2002 the Government announcement the Enhanced Capital Allowance Scheme to allow businesses to claim 100% first year capital allowances on investments in energy saving technologies and products. This would enable businesses to write off the whole cost of their investment against their taxable profits of the period during which they make the investment and encourage businesses to invest in low carbon technologies.

1.10.5 Conclusions

The potential uses of willow SRC are many and varied. This section started with the news of the failure of one of the largest project to date in the UK to utilise willow SRC. In the ARBRE the gasification of willow SRC was to be used to produce 8Mw of electrical power. Many barriers had to be overcome by the ARBRE prior to the commencement of construction, the more obvious being on technical issues and supply procurement. Winning over the agricultural sector to produce what was in effect a new crop to most people was in itself an achievement.

The experience gained from the ARBRE project and from many others across the UK serve only to highlight what is in effect an extremely versatile product whose uses are many varied. Our forefathers have noted its uses for decades for basketry, rope, house building, fencing, beehives, lobster pots and coracle frames. The Celtic Gods considered it to be one of its sacred woods; burning effigies made from willow during important ritual ceremonies and also used it as a fuel and to make charcoal. In Christian times its power was associated with witchcraft, with the broomsticks of witches having a willow shaft and in Perthshire, Scotland the evil spells were reportedly perpetuated by wands made with willow! (Darwin, 1996)

Whilst associated with evil beings willow was also to be associated with good health. Today the main constituent of Aspirin, acetylcalycylic acid is known to be found in the bark of willow. Fifteenth century Scottish physicians in medical texts (Darwin,1996) noted its uses to control bleeding and as a contraceptive, later medicinal uses were to include the use of the bark to treat liver pain, wounds and warts.

The uses of willow over the centuries have been many and varied. Today there is resurgence in this interest in willow. Whilst basketry continues as an end use, its potential as a source of raw material or a feed stock for a variety of industries from energy production, forest industries to chemical production must surely be viewed with an optimism by a society aiming to achieve sustainability with the resources available to us on this planet.

This study aims to consider the potential to utilise disturbed and contaminated sites for the production of willow SRC. The values and benefits of this crop are well documented as are the issues surrounding contaminated and disturbed sites in the UK. This research aims to consider what opportunities could prevail by bringing these two areas together. The potential for the growth of willow on disturbed and contaminated sites is explored through a field trial that seeks to manipulate some of the silvicultural practices employed to grow willows to determine how growth and yield can be effectively maximised.

CHAPTER 2 - ESTABLISHMENT OF FIELD TRIAL AND ANALYTICAL METHODS

2.1 Introduction

Currently, in the UK, returns from growing willow Short Rotation Coppice (SRC) on prime arable land under open market conditions are insufficient to encourage its large-scale adoption. As an alternative to agricultural land, the potential for utilising disturbed industrial land presents significant opportunities. The nature of many of these sites does not lend itself to a high production potential for SRC however, as already noted, when other benefits are bought into the equation, utilising these sites for SRC may have positive impacts.

At present, limitations on growing SRC on such sites is based on the most basic of data. Information on suitable clones for specific sites and silvicultural practices for optimising yields on such sites is extremely limited (Forestry Commission, 1992; Steer & Baker, 1997). Whilst information and data are readily available for growing SRC on agricultural sites, its wholesale translation to industrial and contaminated sites may not always be possible due to the limitations such sites may pose upon individual cultivars of willow.

Constraints, both physical and chemical, imposed by the growing medium into which clones of willow are planted on disturbed industrial sites do not always provide the best environment for the establishment of willow. The need to attempt an assessment of these constraints and to identify potential solutions, in order to optimise the production of willow biomass, is the basis of this field trial.

The need to consider the establishment and success rates of individual clones or cultivars of willow, together with the impact of various silvicultural practices upon their growth rates, all require consideration due to the variability of survival and growth that has been exhibited in trials of willow grown in sewage amended soils (Riddell-Black et al., 1997) in comparison with crops of willow SRC grown in an arable/ grassland settings (Beale &

Haywood, 1997). This field trial considered the different establishment rates between individual clones and the effects of various management techniques that were superimposed upon individual clones.

2.2 The Field Trial

Whilst the prevalence of disturbed and contaminated industrial sites in Scotland and the United Kingdom is well documented (Holgate, 2000; DOE, 1994; Scottish Office, 1990), availability and ease of access to these sites in order to undertake a field trial for research purposes is not as simple a process as it would seem. Various sites were mentioned in the course of conversations with various bodies to find a suitable location, however, gaining permission to use these sites proved problematic, particularly when the field trial period was intended to last 3 years. A site was eventually found and made available by the Greenbelt Group of Companies Limited at Hallside, in Cambuslang, approximately 7 miles south east of the city centre of Glasgow.

2.2.1 The History of the Hallside Steelworks Site

The site of the trial is all that now remains of the vast Hallside Steelworks which covered approximately 33 hectares in its heyday. The steelworks had occupied the site since 1872, when Sir Charles Tennant of the Saint Rollox Chemical Works founded the Steel Company of Scotland with 28 shareholders all connected with heavy engineering or chemical industries. The site was chosen for its ample supply of water from the nearby River Clyde and the proximity of coal and iron deposits, all within easy reach by the rail network located adjacent to the site, and latterly directly to the site. Work at the factory started in 1872 and the first steel was produced by the end of 1873, supplying a variety of industries across Scotland and the former British Empire.

From 1872 up to its closure in 1979 the Hallside Steelworks was one of the major steel producing centres in Scotland. The building of the Forth Railway Bridge in 1889 saw the awarding of a contract to the Hallside Works for the supply of steel used in its construction, one of only three companies awarded contracts to contribute towards the building of the bridge.

Figure 2.1 The Hallside Steelwork in its Heyday

With the closure of the steelworks in 1979, the site was to drift slowly into decline and dereliction. It was left overlain with extensive concrete foundations, open basements and contaminated slag heaps. The derelict appearance of the site, adjacent to the London to Glasgow main railway line, provided visitors to Glasgow with a depressed image and led to a blight on adjacent residential areas. An undertaking to remediate the site at this time would have represented a huge expenditure of public funds. With little or no hope of attracting private investment to the site, even the most basic of remedial options such as capping or removal of the contaminated materials on the site to land fill were estimated to cost in the region of £12 - £30 million (Shepherd, 1996). Even with this inward investment, any chance of attracting commercial development or housing was viewed as slim, given its location and poor access to the motorway road network.

2.2.2 The Proposal

For 16 years the site was a severe environmental problem on the urban fringe of Glasgow. In 1989, a company founded in the public sector but established to consider the potential for re-channelling private money towards the repair and management of the greenbelt or urban fringe of Strathclyde was conceived by the former Strathclyde Regional Council. This company, which today exists as The Greenbelt Group of Companies Limited, was established with one of its remits being to consider the repair of degraded areas in the countryside around town.

Figure 2.2 The Hallside Steelwork Circa 1995

Its attention was focussed on Hallside at an early stage of its development. At the same time as this company was being conceived moves were afoot within the strategic planning authority, again within Strathclyde Regional Council, to identify land suitable for a shortfall in the identified need for housing within Strathclyde. One such site was identified south of the site of the former Hallside steelworks. The site was viewed as a major development opportunity for housing, unfortunately it was located on land designated as greenbelt and directly adjacent to what was a former industrial site.

2.2.3 The Solution

With the establishment of the Greenbelt Company, the council were persuaded to release the greenbelt site for development on the provision that any development on greenbelt land was accompanied by the remediation of the steelworks site to a greenbelt use. This idea was incorporated into the 1990 Strathclyde Structure Plan. After several years of development and planning H J Banks & Company became the lead organisation in the development of the greenbelt land for housing and in the reclamation of the Hallside site.

Figure 2.3 Capping Material Relocated at Hallside

The land identified for housing, whilst being identified as greenbelt, contained two colliery spoils and an inert landfill site on it. These materials were used to form a cap over the former steelworks site that could then be “greened”. The mechanism employed was the creation of new housing to transform a “brownfield” site, the net effect being an increase in the extent of the greenbelt whilst providing in excess of 2000 new homes.

The capping of the derelict Hallside steelworks site involved the movement of 750,000 tonnes of colliery spoil and inert landfill material. At the same time as the earth movement to cap the Hallside site was being implemented, a conundrum was presented to Strathclyde Water (the fore runner of what is today Scottish Water), the provider of clean and foul water services in all of Scotland. The adoption of the Urban Waste Water Treatment Directive (91/271/EEC) in 1991 by the European Union was to impose on the water authorities in the United Kingdom a complete ban on the dumping of sewage sludge into coastal waters.

The former Strathclyde Water Authority were presented with a huge problem, as the disposal route for sewage from the Glasgow conurbation had, for generations, been the daily filling of two ships with raw liquid sewage sludge. This sludge was then shipped down the Clyde and dumped in the sea off the coast of the Isle of Arran in the Firth of Clyde.

With the impending implementation of the Urban Waste Water Directive at the end of 1998, Strathclyde Water had to consider potential alternatives to the sea disposal route. Disposal to agricultural land was a potential solution and indeed the suitability and availability of such land was considered. Sewage sludge in itself is not a contamination free product as it contains elevated concentrations of heavy metals as a consequence of industrial sources of contamination and contamination from household products such as certain hair cleansing products and detergents. Its application to agricultural land is strictly controlled by the Sludge (use in Agriculture) Regulations 1989. Various alternative disposal routes were considered which presented both positive and negative benefits. One such route was its potential use in the remediation of disturbed and contaminated industrial sites. It was this route that was tested at Hallside.

The soil medium used in the capping of Hallside was in itself a poor growing medium. To encourage the rapid establishment of the site, the addition of inorganic fertilisers could have been viewed as beneficial, however the cost would have been hugely expensive. Digested sewage sludge cake containing approximately 25% solids was, however, a free source of fertiliser and a good source of organic matter to assist in the development of an improved soil structure. Approximately 10,000 tonnes of digested sewage sludge cake were incorporated into the growing medium, providing a valuable nutrient addition, and in the process testing the potential of land reclamation projects as a sustainable disposal route. The application rate for the sewage sludge was pre-determined by the Greenbelt Company in accordance with unpublished draft guidance produced by the Water Research Council on the application rates for sewage sludge onto disturbed and contaminated sites (WRC, 1995). The Greenbelt Company were then to plant and manage the site on a 99 year lease.

Figure 2.4 Hallside Steelworks Today

It was within this growing medium of inert landfill material and colliery spoil, amended with sewage sludge, that a field trail was established to consider the potential of disturbed, contaminated and derelict industrial sites for the production of willow SRC.

Analytical data for both the colliery spoil and the sewage cake (used to cap the site) are shown in Table 2.1 and 2.2. (Craven, 1997 Pers Comm). Analysis of the underlying surface, prior to capping, indicated heavy metal levels far in excess of those materials used for capping. Table 2.3 gives an indication of the range of heavy metals recorded on the site prior to capping, which is considered indicative of the heterogeneity that is often associated with such locations (Richard et al, 1993).

Table 2.1 Analysis of Pit Spoil Material from the two colliery spoil heaps (Craven, 1997 Pers Comm)

	Dechmont Spoil		**Dechmont Spoil**	
	Top Soil	**Sub Soil**	**Top Soil**	**Sub Soil**
Depth cm	0-20	50-70	0-20	50-70
% loss on ignition	24.6	17.6	28.0	29.9
pH water	6.2	6.1	5.8	6.9
pH $CaCl_2$	6.1	6.0	5.4	6.7
% carbon	14.5	7.74	15.9	20.7
% nitrogen	0.24	0.11	0.37	0.37
P_20_5 mg kg^{-1}	113.7	129.7	250.7	104.7
Cadmium (Cd)	0.84	0.62	0.92	1.19
Chromium (Cr)	0.12	0.61	0.38	0.04
Copper (Cu)	38.0	24.0	20.0	18.0
Manganese (Mn)	96.0	104.0	191.0	251.0
Nickel (Ni)	4.2	2.5	6.5	4.2
Lead (Pb)	182.0	62.0	82.0	103.0
Zinc (Zn)	95.5	17.4	113.0	137.0

*All Trace Elements obtained by 0.05m Extractable EDTA in mg kg^{-1}

Table 2.2 Strathclyde Sewage Daldowie STW Centrifuge Trial Analysis Weekly Composite Samples (Craven, 1997 Pers Comm)

Analysis	**Week Commencing 14.2.94 Feed**	**Week Commencing 14.2.94 Cake**	**Week Commencing 21.2.04 Feed**	**Week Commencing 21.2.04 Cake**
pH	7.8	7.4	7.7	7.9
% Dry Solids	1.9	33.6	1.9	32.9
Organic Matter (%)	53.8	56.5	54.6	56.4
Total Nitrogen (%)	7.15	3.32	6.05	3.98
P_2O_5 (mg kg^{-1})	3.31	3.17	3.18	3.62
K_2O (mg kg^{-1})	0.72	0.25	0.19	0.24
Cd	4	3	2	2
Cr	99	87	82	88
Cu	408	447	312	358
Pb	267	179	230	249
Hg	1.8	2	2.1	2.7
Ni	79	72	55	58
Zn	649	706	621	666

Key

All Metal concentrations are in mg kg^{-1} . Feed refers to the untreated sewage entering the Sewage Treatment Works whereas cake refers to the digested and dewatered sewage (using a centrifuge). Only two weeks worth of data are shown. These are deemed to be representive of the chemical quality of sewage sludge at the works at the time.

Table 2.3 Total Heavy Metal Concentration Ranges for Hallside Prior to Capping (Craven, 1997 Pers Comm)

Metal	Range (mg kg^{-1})
Cadmium	<1 - 22.8
Lead	57 - 667
Copper	26 - 460
Nickel	28 – 295
Zinc	117 – 1276
Chromium	59 – 559

2.3 The Hallside Field Trial

The proposal for the establishment of a SRC Field Trial on the former Hallside Steelworks Site, Cambuslang, Glasgow, centred upon the need to consider the optimal conditions for growing willow SRC utilising a variety of available management techniques in conjunction with 5 willow clones, i.e. to optimise the yield of willow SRC grown under these constrained growing conditions with only changes in clones and the silvicultural practices being employed.

A trial was established which addressed the use of 4 management techniques upon the growth of 5 clones of willow SRC. While these silvicultural practices are common or prevalent for the growth of willow on agricultural land (Macpherson, 1995), the availability of information for growing willow in poor growth media is limited. This trial was established to consider:

(i) The effect of weed control treatments upon the SRC yield.

Experience in field trials undertaken by work colleagues growing willow SRC on disturbed and contaminated sites indicated that the soil structure and nature of the weed competition on such sites had caused considerable problems in the establishment of willow. The implication of weed control in the growth of willow is well documented, however as this trial considered the potential for growing willow as an alternative remediation strategy for contaminated and disturbed sites, the need to consider whether weed control is effective and indeed viable under such conditions was considered necessary.

(ii) The use of inorganic fertiliser to promote coppice growth and subsequent yields.

Growth conditions on disturbed and contaminated sites are known to be limiting due to the nature of the growing medium e.g. low nutrient values or contaminants that may limit growth. Whilst an addition of sewage sludge was known to have occurred, the addition of an inorganic fertiliser was also employed to consider whether there would be any increased benefits on willow production from its addition and to assess whether the benefits could be justified on such a low input site.

(iii) The implication of stool spacing upon yields.

The implication of stool spacing as a tool to increase yield (Bullard et al., 2002) was considered appropriate to gauge the benefit (if any) of the density of planting when assessed against yields from such difficult sites. Could an increase in planting density be justified simply by the increased volume of biomass harvested, or was increasing the planting density unviable, with little or no significant benefits in terms of increased yields from its use on such sites?

(iv) The influence of coppicing upon yield.

Coppicing after the first year's growth is a tried and tested process in the growth of willow SRC (Ferm, 1990). Personal communication with operators growing willow on disturbed and contaminated sites had suggested the coppicing of willow after the first year's growth on such poor sites affected the survival of the willow. It was suggested that this was due to poor root establishment. The need for continued use of herbicide to ensure the survival of coppiced stools represents a major cost input on such sites. By altering the time of the first coppice, the field trial considered the appropriateness of coppice timing upon yield and whether, on contaminated and disturbed sites, a longer period should be employed before the initial coppice.

Figure 2.5 The Field Trial at Hallside

In order to assess the influence of all the treatments upon 5 individual clones of willow, 3 replicated randomised blocks were planted, separated from each other by a 5m gap. Each block contained 24 plots. This was calculated from the need to assess the effect of the 4 silvicultural practices upon the yield of willow SRC. The treatments adopted were -

1. The effect of chemical weed control against no weed control.
2. The use of inorganic fertiliser against no additional fertilisation input.

3. Varying the planting densities of Willow stools by planting at 0.5m and 1.0m centres.
4. Coppicing the clones at 3 different time periods i.e. the end of Year 1, Year 2 and Year 3.

The site was laid out as follows:

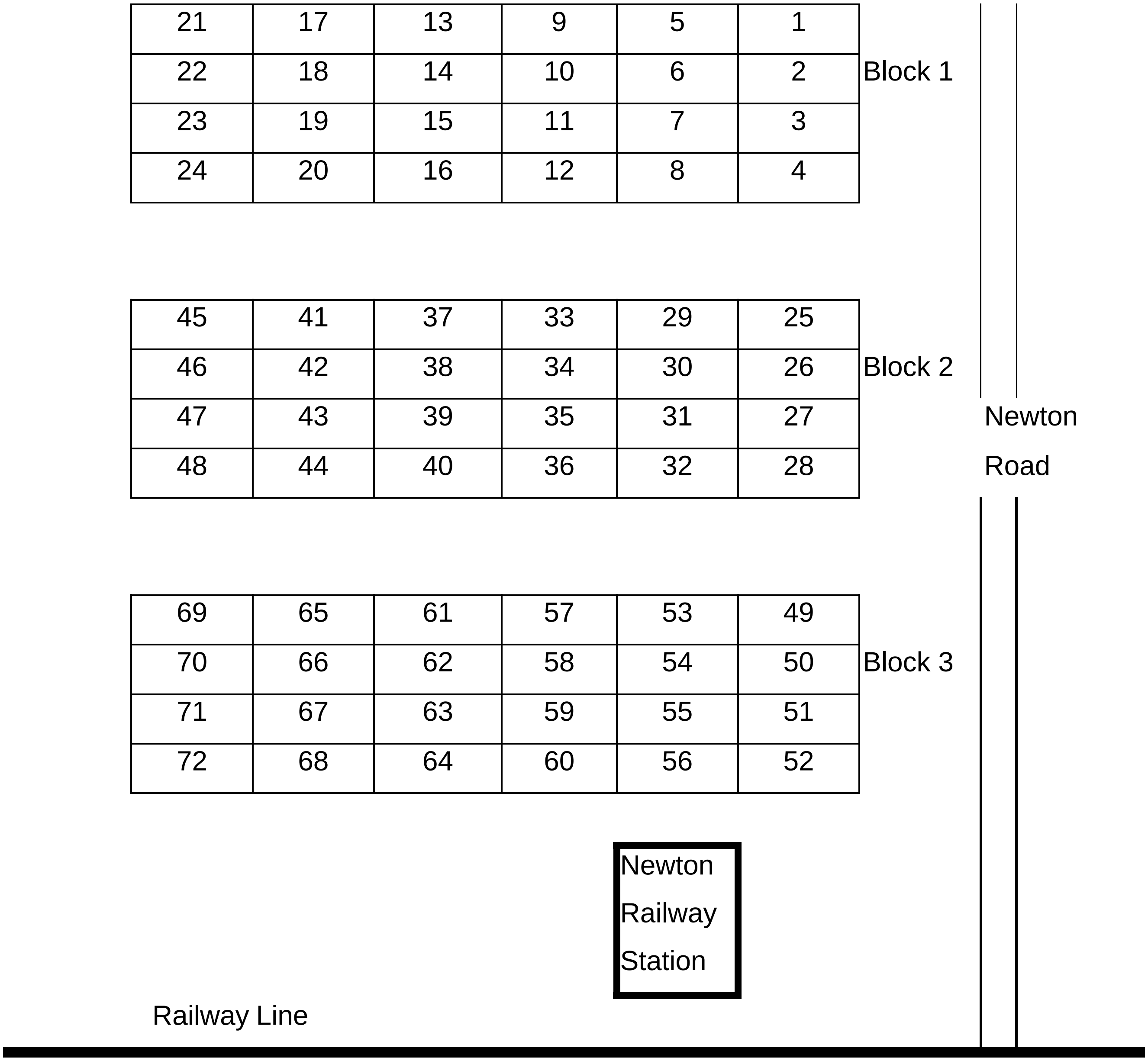


Figure 2.6 Sketch Map of The Hallside Willow Short Rotation Coppice Field Trial Showing the Individual Plot Numbering and Block Layout

Within each plot the following 5 clones of willow were planted in rows -

Table 2.4 Willow Clones Used in the Field Trial

Code	**Common Name**	**Parentage**	**Sex**	**Use**
A	Rosewarne White	*S. aurita x cinerea x viminalis*	?	BK
B	Burjatica Germany	*S. burjatica*	F	Bio
C	Dasyclados	*S. caprea x cinerea x viminalis*	F	Bio
D	Gigantea	*S.viminalis*	M	Bio
E	Spaethii	*S.spaethii*	F	?

Key

M – Male	BK – Basket Willow
F – Female	Bio Biomass
? – Unknown	

The selection of willow clones employed for the trial plots was based upon existing studies growing willow on sewage sludge amended soils in Nottinghamshire. (Riddell-Black et al., 1997). The clones selected reflected a cross section ranging from those that had been successful/ unsuccessful in metal accumulation and those that had produced large/small volumes of biomass.

The use of contract labour (who were undertaking the planting of areas adjacent to the field trial) imposed constraints upon the planting design. This resulted in the first two columns of each block being planted at staggered 0.5 m centres, and the final two columns being planted at 1.0 m centres with no rotation in the planting position of the clones within each plot being possible

Two size options for the plots were considered initially when the trial was being planned, these were:

(i) Individual plots measuring 5.5 m x 10.5 m plots giving a total area requirement of 0.42 hectare

(ii) Individual plots measuring 5.5 m x 5.5 m plots giving a total area requirement of 0.22 hectare

As the Greenbelt Group of Companies Limited had kindly made available land for the study on a site which had previously occupied 33 hectare the former option (larger plots) was used. Each plot was planted as follows –

A	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**
B	B	B	B	B	B	B	B	B	B
C	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**
D	**D**	**D**	**D**	**D**	**D**	**D**	**D**	**D**	**D**
E	**E**	**E**	**E**	**E**	**E**	**E**	**E**	**E**	**E**

Figure 2.7 Sketch Diagram of the Planting Regime imposed on each 10.5 x 5.5 m plot at 1.0 m density

Key:

A, B, C, D, E - Individual stools of same clone planted at 1m centres where A = Rosewarne White, B = Burjatica Germany, C = Dasyclados, D = Gigantea and E = Spaethii

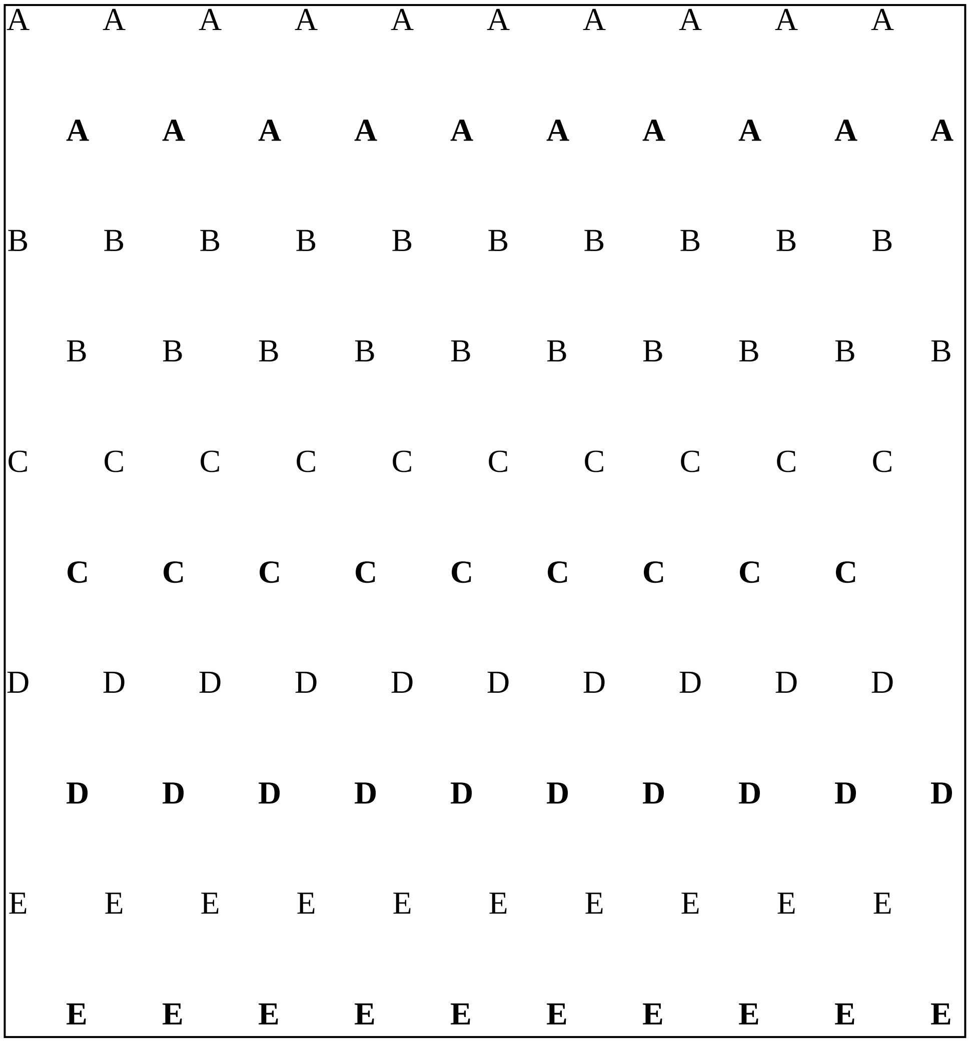


Figure 2.8 Sketch Diagram of the Planting Regime imposed on each 10.5 x 5.5 m plot at 0.5 m density

Key:

A, B, C, D, E - Individual stools of same clone planted at 1m centres where A = Rosewarne White, B = Burjatica Germany, C = Dasyclados, D = Gigantea and E = Spaethii

The need to consider the effect of all treatments upon 5 individual clones of willow resulted in 3 replicated blocks. The treatments to be employed on each plot within each block were randomly selected. The final plot layout within each individual block is shown in Figure 2.9 – 2.11.

Block 1	Fertiliser Chemical weed cont'l 1 year rotation	No fertiliser No weed control 2 year rotation	No fertiliser Chemical weed cont'l 2 year rotation	Fertiliser No weed control 3 year rotation	No fertiliser No weed control 3 year rotation	Fertiliser Chemical weed cont'l 2 year rotation	0.5m spacing
	No fertiliser Chemical weed cont'l 3 year rotation	Fertiliser Chemical weed cont'l 3 year rotation	No fertiliser No weed control 1 year rotation	Fertiliser No weed control 1 year rotation	Fertiliser No weed control 2 year rotation	No fertiliser Chemical weed cont'l 1 year rotation	0.5m spacing
	Fertiliser No weed control 3 year rotation	No fertilizer Chemical weed cont'l 3 year rotation	No fertiliser No weed control 3 year rotation	Fertiliser Chemical weed cont'l 2 year rotation	No fertiliser No weed control 2 year rotation	Fertiliser No weed control 1 year rotation	1.0m spacing
	Fertiliser Chemical weed cont'l 1 year rotation	No fertiliser Chemical weed cont'l 1 year rotation	Fertiliser Chemical weed cont'l 3 year rotation	No fertilizer Chemical weed cont'l 2 year rotation	Fertiliser No weed control 2 year rotation	No fertiliser No weed control 1 year rotation	1.0m spacing

21	17	13	9	5	1
22	18	14	10	6	2
23	19	15	11	7	3
24	20	16	12	8	4

Figure 2.9 Plot Layout Within Block 1

Block 2	Fertiliser Chemical weed cont'l 2 year rotation	No fertiliser Chemical weed cont'l 1 year rotation	No fertiliser No weed control 1 year rotation	Fertiliser No weed control 2 year rotation	Fertiliser No weed control 3 year rotation	No fertiliser No weed control 2 year rotation	0.5m spacing
	Fertiliser No weed control 1 year rotation	Fertiliser Chemical weed cont'l 3 year rotation	Fertiliser Chemical weed cont'l 1 year rotation	No fertilizer Chemical weed cont'l 2 year rotation	No fertiliser Chemical weed cont'l 3 year rotation	No fertiliser No weed control 3 year rotation	0.5m spacing
	No fertiliser Chemical weed cont'l 2 year rotation	Fertiliser Chemical weed cont'l 2 year rotation	Fertiliser No weed control 1 year rotation	Fertiliser No weed control 3 year rotation	No fertiliser Chemical weed cont'l 3 year rotation	No fertiliser No weed control 3 year rotation	1.0m spacing
	Fertiliser Chemical weed cont'l 3 year rotation	Fertiliser Chemical weed cont'l 1 year rotation	No fertiliser No weed control 2 year rotation	Fertiliser No weed control 2 year rotation	No fertiliser No weed control 1 year rotation	No fertiliser Chemical weed cont'l 1 year rotation	1.0m spacing

45	41	37	33	29	25
46	42	38	34	30	26
47	43	39	35	31	27
48	44	40	36	32	28

Figure 2.10 Plot Layout Within Block 2

Block 3	Fertiliser Chemical weed cont'l 3 year rotation	No fertiliser Chemical weed cont'l 3 year rotation	No fertiliser Chemical weed cont'l 2 year rotation	No fertiliser No weed control 1 year rotation	No fertiliser Chemical weed cont'l 1 year rotation	Fertiliser No weed control 3 year rotation	0.5m spacing
	No fertiliser No weed control 3 year rotation	Fertiliser Chemical weed cont'l 1 year rotation	Fertiliser Chemical weed cont'l 2 year rotation	No fertiliser No weed control 2 year rotation	Fertiliser No weed control 2 year rotation	Fertiliser No weed control 1 year rotation	0.5m spacing
	Fertiliser Chemical weed cont'l 3 year rotation	No fertiliser Chemical weed cont'l 2 year rotation	Fertiliser No weed control 1 year rotation	No fertiliser No weed control 1 year rotation	Fertiliser No weed control 2 year rotation	No fertiliser Chemical weed cont'l 1 year rotation	1.0m spacing
	No fertiliser Chemical weed cont'l 3 year rotation	Fertiliser No weed control 3 year rotation	Fertiliser Chemical weed cont'l 2 year rotation	Fertiliser Chemical weed cont'l 1 year rotation	No fertiliser No weed control 3 year rotation	No fertiliser No weed control 2 year rotation	1.0m spacing

69	65	61	57	53	49
70	66	62	58	54	50
71	67	63	59	55	51
72	68	64	60	56	52

Figure 2.11 Plot Layout Within Block 3

2.4 Fertiliser Application

As has already been noted the site to be used for the field trial consisted of colliery spoil and landfill material with a dressing of sewage sludge cake (25% Dry Solids.) applied at a rate of approximately 300 tonnes ha^{-1} and ripped into the growing medium. Additional fertiliser was applied to individual plots to consider whether there would be additional benefits to the willow from its application. With hindsight, it is noted that an assessment of the fertility of the growing medium would have been beneficial prior to the establishment of the field trial and the addition of the fertiliser, however, time constraints at the planting period necessitated the addition of the inorganic fertiliser without recourse to the growing medium's fertility.

As has been noted previously, the addition of an inorganic fertiliser was also employed to consider whether there would be any increased benefits on willow production from its addition and to assess whether the benefits could be justified on such a low input site.
To those plots selected to receive the fertiliser treatment an additional application of NPK (20:20:10) fertiliser was applied on an annual basis. This was applied by hand at a rate of 100 kg ha^{-1} or 0.583 kg per individual plot.

2.5 Weed Control

A stringent weed control program was initiated in all three years of the field trial, utilising a back mounted knapsack sprayer. Initially, *Dash* (ammonium glufosinate) was applied. An additional application was applied in the first year due to the questionable success of the first application. As the establishment of the field trial had been undertaken on what was previously a virgin site, the nature of the weeds present could not be determined.

Figure 2.12 Hallside Field Trial Showing the Weed Invasion

With the progression of the first growing season, the more dominant weed species was noted as the spiny Scentless Mayweed (*Matricaria maritima, Matricaria chamomilla or Matricaria matricoroides)* commonly known as the pineapple weed. Whilst the herbicide had some effect on this weed it had not succeeded in eradicating the problem. An additional application was made following consultation with Peter Barclay of Nomix-Chapman Limited, distributors of herbicide and suppliers of technical information, who recommended the effectiveness of *Dash* to counter scentless mayweed, but noted that the leaf surface may not permit sufficient water to penetrate and kill the weed. If a repeated application was not successful, a glyphosate based herbicide was recommended, however, some practitioners in the willow SRC field consider this to be ill advised as even a tiny amount of glyphosate drift can severely endanger willow.

During a visit to a commercial willow plantation in Nottingham in June 2000, it was noted that mechanical spraying of glyphosate took place across the entire plantation. The farmer concerned noted that the willow SRC was checked for a week by the application of the glyphosate, however, he indicated that in low concentrations (the exact concentration was not provided, but had been obtained via their own trials) that the willow recovered and the weeds were either killed or checked. Care was recommended in its use, however, comments from the farmer concerned seemed to indicate that it was the only chemical herbicide that provided an adequate solution to the weed invasion issues in the initial establishment year.

A second application of Dash again showed only limited success. Consultation with the Water Research Centre (Drusilla Riddell-Black, 1997 Pers. Comm.) indicated that they had similar problems with scentless mayweed and a recommendation to use *Dow Shield* (a Clopyralid based herbcide) was provided. An application rate of 100 ml per 20 l was recommended as sufficient to cover approximately 1000 m^2 (1 litre ha^{-1}). Greater success was noted with the use of *Dow Shield* and its use was continued for the second and third years of the trial. Field observations in the second and third years of the trial indicated that scentless mayweed posed far less of a problem on the site, with thistles, nettles and grass being the more dominant weed species.

2.6 Measurements & Harvesting

Measurements of the survival, heights, diameters (at half the total shoot height) and number of shoots produced from each of the willow SRC stools were taken throughout the growing period in the first year, thereafter in years two and three, at the end of the growing season.

The manual harvest and weighing of selected plots was undertaken in December or January of each year with the yields being recorded in the field by means of a weighing rig fabricated by the University of Glasgow Works department (see Photograph 2.9) or if sufficiently small (as in the first year) whole samples were returned to the lab for measurement. All samples weighed in the field were sub-sampled and returned to the laboratory for dry weight determination and wood and bark heavy metal analysis. To allow comparison of yields between those plots harvested on an annual basis and those harvested at 2 and 3 year intervals, the cumulative yield values for three years growth are noted in the results section.

Figure 2.13 Harvesting operations at Hallside

Figure 2.14 Harvesting and Sample Collection at Hallside

Figure 2.15 Field Weighing of Harvested Material at Hallside

2.7 Additional Clone Testing

In addition to the field trial, approximately 20 double rows (adjacent to the field trial) of individual willow clones at 1 m centres, planted at the same time as the field trial by the Greenbelt Group of Companies Limited, were tagged for identification (Table 2.5 and 2.6). These double rows extended for distances in excess of 100 m across two locations on the site. No treatments were superimposed onto these tagged lines apart from some chemical and physical weed control implemented by the site owners. At the end of the first growing season, the survival, growth rates and yields of the clones were assessed. As little control had been possible as to the planting design of the tagged lines, all measurements and samples were taken across the entire length of the tagged lines at intervals of 10-20 m, 30-40 m and 50-60 m.

Table 2.5 Varieties of Tagged Willow in Area S (adjacent to the Newton Railway Station)

Code	**Common Name**	**Parentage**	**Sex**	**Use**
1.	Gigantea	*S.viminalis*	M	Bio
2.	Stipularis	*S. stipularis*	?	?
3.	Orm	*S.viminalis*	?	Bio
4.	Rapp	*S.viminalis*	?	?
5.	Dasyclados	*S. caprea x cinerea x viminalis*	F	Bio
6.	Tora	*S.viminalis x schwerinii*	?	Bio
7.	Coles	*S. caprea x cinerea*	M	Bio
8.	Ulv	*S. viminalis*	?	SRC
9.	Q83	*S. triandra x viminalis*	F	Bio
10.	Rosewaren White	*S. aurita x cinerea x viminalis*	?	BK
11.	Calodendron	*S. caprea x viminalis x cinerea*	F	Bio
12.	Jorunn	*S. viminalis*	?	Bio
13.	77699	*S. viminalis*	?	Bio
14.	Cambell 3106	*S. viminalis*	F	?
15.	Spaethi	*S. spaethii*	F	Bio
16.	Niginians Prunifolia	*S. caprea x viminalis*	M	?
17.	Candida	*S. candida*	M	Bio
18.	Delamere	*S. aurita x cinerea x viminalis*	?	Bio

Key

M – Male	? - unknown	BK – Basket Willow
F – Female	Bio – Biomass	

Table 2.6 Varieties of Tagged Willow in Area V (adjacent to the Hallside village)

Code	**Common Name**	**Parentage**	**Sex**	**Use**
1.	Q83	*S. triandra x viminalis*	F	Bio
2.	Calodendron	*S. caprea x viminalis x cinerea*	F	Bio
3.	Jorunn	*S.viminalis*	?	Bio
4.	Cambell 3106	*S.viminalis*	F	?
5.	Spaethii	S. spaethii	F	Bio
6.	Niginians Prunifolia	*S. caprea x viminalis*	M	?
7.	Candida	*S. candida*	M	Bio
8.	Delamere	*S. aurita x cinerea x viminalis*	?	Bio
9.	Tora	*S.viminalis x schwerinii*	?	Bio
10.	Bjorn	*S. viminalis x schwerinii*	?	Bio
11.	Delamere	*S. aurita x cinerea x viminalis*	?	Bio
12.	Gigantea	*S.viminalis*	F	Bio
13.	Stipularis	*S. stipularis*	?	?
14.	Bjorn	*S.viminalis x schwerinii*	?	Bio
15.	Orm	*S.viminalis*	?	Bio
16.	Rapp	*S. viminalis*	?	?
17.	Dasyclados	*S. dasylados*	M	Bio
18.	Jor	*S. viminalis*	?	?
19.	Coles	*S. caprea x cinerea*	M	Bio
20.	Ulv	*S. viminalis*	?	Bio

Key

M – Male ? - unknown BK – Basket Willow

F – Female Bio – Biomass

The clones that were tagged on the two areas adjacent to the experimental blocks represent a mixture of willow cultivars and include what are termed the unimproved and improved varieties (i.e. the more recent high yielding varieties). Regrettably the lack of control as to the planting layout has not enabled an exact replication in the planting in both areas. Statistical comparison between the two areas has proved problematic; however, observations and broad comparisons have been made. Experience gained from these two areas has, however, proven of value when considering their suitability for growing on disturbed and contaminated sites.

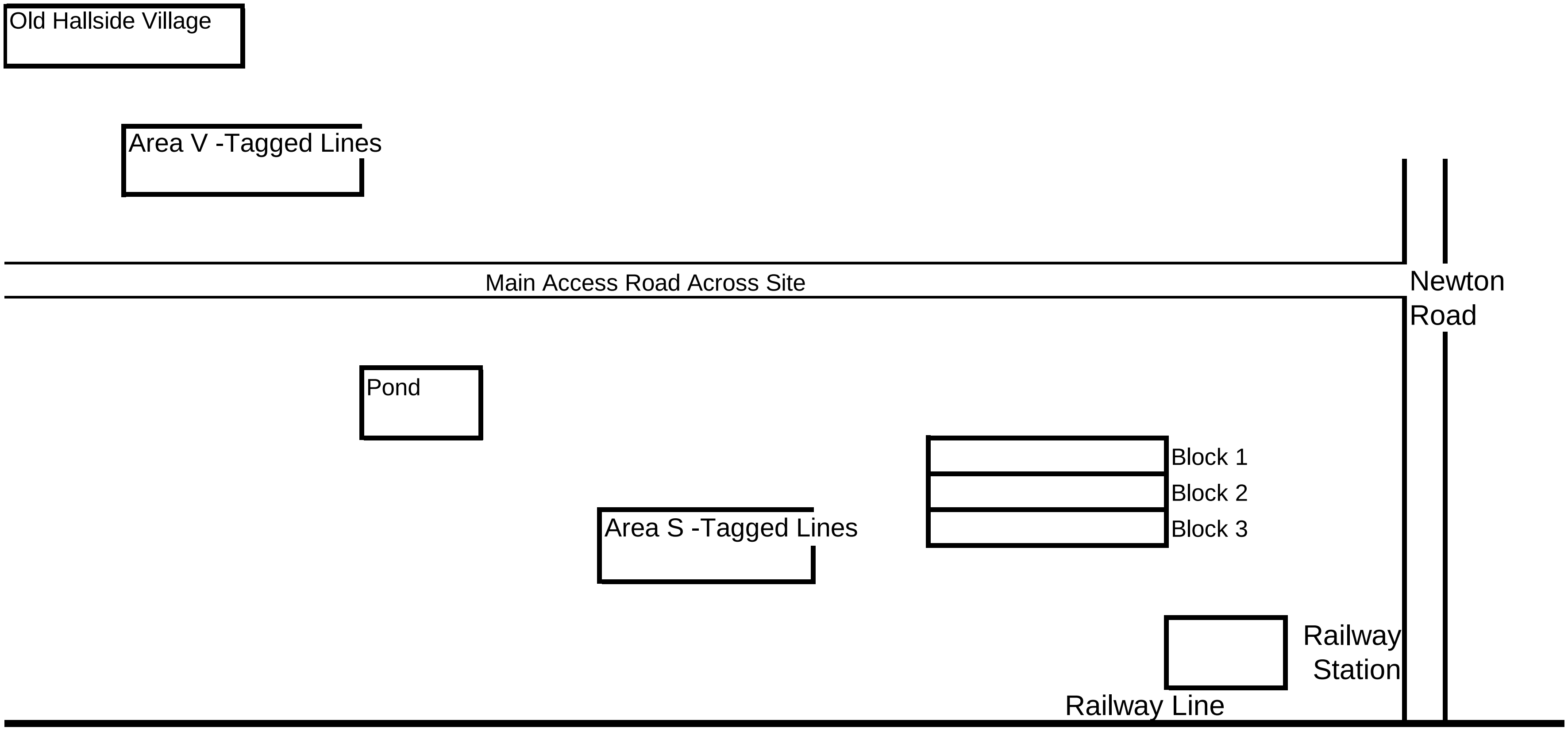


Figure 2.16 Sketch Map of The Hallside Willow Short Rotation Coppice Field Trial Showing the Block Layout and the V and S Areas of the Tagged Willow Clones

2.8 Growing Medium Analysis

Prior to the establishment of the field trial, soil samples were collected to determine the heavy metal concentrations in the growing medium. The concentration of six metals were assessed as part of this exercise, these were Nickel (Ni), Zinc (Zn), Lead (Pb), Copper (Cu), Chromium (Cr) and Cadmium (Cd).

2.8.1 Sample Collection, Preparation and Analysis

Twelve random samples, four from each block, were collected to a depth of 30 cm in the growing medium. All samples were double bagged and returned to the laboratory for analysis. Prior to analysis each individual sample was air dried and sieved through a 2 mm mesh sieve and sub samples ground with a mortar and pestle. Triplicate samples of the ground material weighing approximately 0.25-1.00 g were weighed using a four place analytical balance and placed in block digestion tubes.

To each block digestion tube was added 10 ml of aqua regia solution, (a solution of 3:1 hydrochloric acid/ nitric acid containing 6 molar hydrochloric acid to 69% nitric acid). Each tube was allowed to stand for a minimum of 12 hours to allow the acid to equilibrate with the growing medium. After standing, the tubes were heated to a temperature of 125^{o}C and the extraction unit switched on to remove the brown NO_2 gas evolved during the digestion.

After a period of 3 hours or until the tubes are clear of brown nitrogen dioxide gas, the digests were allowed to cool and 10 ml of deionised water added. The digest remaining in the tubes were filtered together with the washings from each tube into 25ml volumetric flasks. Each volumetric flask was made up to volume using deionised water and the samples measured against pre determined standard solutions using the Perkin Elmer 1100B atomic absorption spectrophotometer.

2.9 Heavy Metal Analysis of the Plant Tissue

2.9.1 Sample Collection, Preparation and Analysis

Analyses of all biomass (wood and bark) and leaf material for heavy metal content were undertaken according to the following method: Prior to the digestion of any plant material, all samples were initially washed with deionised water to remove any dust particles and air dried on the workbench. After the initial bench drying, all samples were oven dried at approximately 80°C overnight. Once the plant material was dry it was ground to less than 1.5 mm using an electric grinder and sealed in self-sealing storage bags in readiness for digestion. Triplicate samples weighing approximately 0.25-0.5 g were weighed accurately using a four-place balance and placed in a block digestion tube.

To each block digestion tube was added 10 ml of 69% nitric acid. Each tube was allowed to stand for a minimum of 12 hours to allow the acid to equilibrate with the plant material. After standing, the tubes are heated to a temperature of 120°C and the extraction unit is switched on to remove the brown NO_2 gas evolved during the digestion.

After a period of 3 hours or until the tubes are clear of brown nitrogen dioxide gas the digests are allowed to cool and 10 ml of deionised water added. The digest remaining in the block digestion tubes were filtered together with the washings from each tube into 25 ml volumetric flasks. Each volumetric flask was made up to volume using deionised water and the samples measured against pre determined standard solutions using the Perkin Elmer 1100B atomic absorption spectrophotometer unit.

2.10 Preparation of Calibration Standards

All atomic absorption standards were prepared from purchased standard solutions.
The standards were “Spectrosol” (BDH laboratory supplies) or “Fisons”
Standard metal solutions. All stock solutions were 1000 $\pm$ 2 mg 1^{-1} certified solutions.
These stock solutions were used to prepare both calibration and check standards.

Cadmium

The linear range for cadmium on the Perkin Elmer 1110B spectrophotometer in normal Acetylene/Air Flame mode was 0 to 2 mg 1^{-1}. Four calibration standards were prepared (0.5, 1.0, 1.5 and 2.0 mg 1^{-1}).

Copper

The liner range of copper on the Perkin Elmer 1100B spectrophotometer in normal Acetylene /Air Flame mode was 0 to 5 mg 1^{-1}. The procedure was to prepare 5 standards (1, 2, 3, 4 and 5 mg 1^{-1}).

Chromium

The linear range for chromium on the Perkin Elmer 1100B spectrophotometer in normal Acetylene/Air Flame mode was 0 to 5 mg $1^{-1.}$ The procedure was to prepare 5 standards (1, 2, 3, 4, and 5 mg$1^{-1)}$.

Lead

The linear range for lead on the Perkin Elmer 1100B spectrophotometer in normal Acetylene/Air Flame mode was 0 to 20 mg 1^{-1}. The procedure was to prepare 4 standards (5, 10, 15 and 20 mg 1^{-1}).

Nickel

The linear range for Nickel on the Perkin Elmer 1100B spectrophotometer in normal Acetylene/Air Flame mode was 0 to 2 mg 1^{-1}. Four calibration standards were prepared (1, 2, 3 and 5 mg 1^{-1})

Zinc

The linear range for zinc on the Perkin Elmer 1100B spectrophotometer in normal Acetylene/Air Flame mode was 0 to 1 mg 1^{-1}. Due to the limited linear range the calibration graph was extended beyond the linear to 5 mg 1^{-1}. Seven calibration standards were prepared (0.5, 1.0, 1.5, 2.0, 3.0, 4.0 and 5.0 mg 1^{-1}).

CHAPTER 3 - RESULTS

3.0 Introduction

Data collected from the field trial undertaken at the former Hallside Steelworks Site are presented in this chapter together with results from all laboratory analyses undertaken. The data presented represent results collected from a three year field trial addressing the survival, growth rates and yields obtained from the range of silvicultural treatments that were superimposed upon individual plots within the field trial. In addition to the field trial, data are presented from the additional clones assessed out with the treatment plots. Due to the large volume of data collected only the abbreviated results are shown in this chapter. The full data sets are provided in Annex 1.

3.1 Metal Concentrations in the Growing Medium

Samples for the analysis of the heavy metal concentrations in the growing medium were collected from each replicate block of the trial where no silvicultural treatments were undertaken.

Analysis of the heavy metal content of the growing medium indicated that the range of concentration for each heavy metal varied across the area of the field trial. With reference to the Inter Departmental Committee on the Reclamation of Contaminated Land (ICRCL, 1987) guidelines, (see Table 1.1), cadmium, chromium and lead concentrations were all within threshold concentration values for determining the sites suitability for use as a domestic garden or allotment.

Reference to the ICRCL (1987) values indicated that the trigger threshold values are exceeded for the metals nickel, zinc and copper. The concentration of nickel was elevated in all 12 samples with the concentration ranging between 77.2 and 107.2-mg kg^{-1}. The highest concentration was recorded in the sample taken from plot 15. Zinc was elevated in all 12 plots sampled with concentrations ranging from 309.6 and 889.9-mg kg^{-1}. The highest concentration was noted for plot 45. Copper exceeded the threshold values in seven of the twelve plots sampled. The highest concentration for copper 200.5-mg kg $^{-1}$ was recorded in plot 32. All other metals analysed were below threshold values. Cadmium is excluded from the results as it was below the detectable limit on the spectrophotometer.

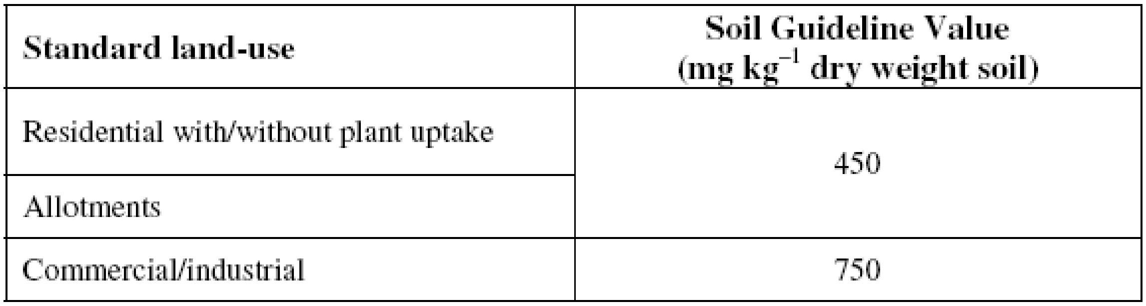
For the elements copper, nickel and zinc the significance of the threshold values being exceeded becomes important as the values are threshold values for any uses where plants might be grown. Concentrations above these levels might be considered as phytotoxic and inhibiting to the growth of certain plant species.

In 2002 guidelines for use in making an informed judgement as to the need for intervention prior to the use of contaminated sites in the UK adopted the CLEA model to provide an assessment of risks to human health from soil contamination (DEFRA, 2002). A consequence of these guidelines has been the publication of Soil Guideline Values (SGV) for individual substances. Not all substances have SGVs and where no values are published, practitioners in the field are recommended to undertake a risk assessment of site – specific criteria, the result of which should be used to inform the decision-making process.

SGVs have been published for four of the heavy metals considered in this study. These are cadmium, nickel, lead and chromium. Tables 3.1 to 3.4, reproduced below, provide comparison of the metal concentrations recorded at the site of the field trial with available SGVs. Nickel represents the only metal concentration to exceed the available SGV. The intervention value is exceeded where the intended land use is for residential or allotment purpose only.

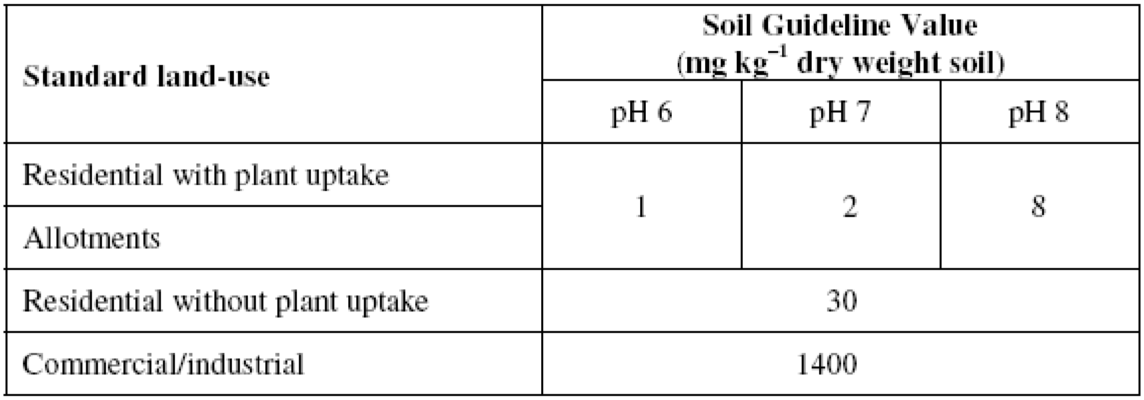
No SGVs were available for zinc and copper. Commercial practitioners requiring values for zinc and copper would be required to calculate them using the CLEA software, which follows the methodology laid out in Contaminated Land Reports (CLR) 7-10 or alternatively employ companies such as Atrisksoil, which provide an online database providing SGVs for common contaminants not currently covered by available reports.

Table 3.1 Soil Guideline values for Lead as a Function of Land Use (DEFRA & EA, 2002)



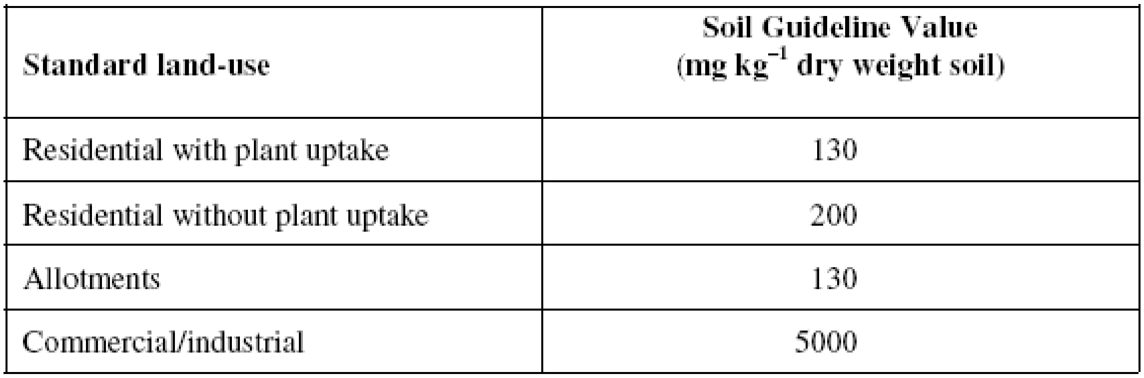
Standard land-use	**Soil Guideline Value (mg kg^{-1} dry weight soil)**
Residential with/without plant uptake	450
Allotments	
Commercial/industrial	750

Table 3.2 Soil Guideline values for Cadmium as a Function of Land Use (DEFRA & EA, 2002)



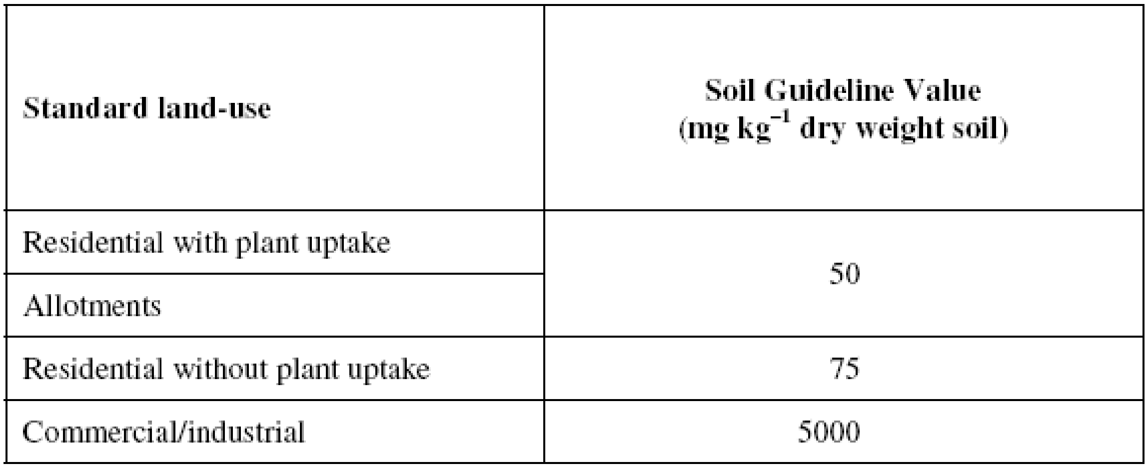
Standard land-use	**Soil Guideline Value (mg kg^{-1} dry weight soil)**		
	pH 6	pH 7	pH 8
Residential with plant uptake	1	2	8
Allotments			
Residential without plant uptake	30		
Commercial/industrial	1400		

Table 3.3 Soil Guideline values for Chromium as a Function of Land Use (DEFRA & EA, 2002)



Standard land-use	**Soil Guideline Value (mg kg^{-1} dry weight soil)**
Residential with plant uptake	130
Residential without plant uptake	200
Allotments	130
Commercial/industrial	5000

Table 3.4 Soil Guideline values for Nickel as a Function of Land Use (DEFRA & EA, 2002)



Standard land-use	**Soil Guideline Value (mg kg^{-1} dry weight soil)**
Residential with plant uptake	50
Allotments	
Residential without plant uptake	75
Commercial/industrial	5000

Table 3.5 Total Heavy Metal Concentrations for the Growing Medium in mg kg $^{-1}$ dry weight soil at the Hallside Field Trial

Plot Reference	Ni	Zn	Pb	Cu	Cr	Cd
7	93.2	464.0	167.6	165.9	69.4	Bdl
15	135.1	265.0	66.8	93.6	56.2	Bdl
20	104.4	435.4	138.9	192.1	75.0	Bdl
21	107.2	423.0	182.3	121.5	66.8	Bdl
27	95.8	409.2	151.2	159.4	74.0	Bdl
32	103.1	594.6	167.1	200.5	88.6	Bdl
42	90.2	240.1	85.9	113.0	57.5	Bdl
45	83.9	889.9	113.8	123.7	76.4	Bdl
50	92.2	409.2	140.7	161.4	78.7	Bdl
60	86.8	309.6	121.7	120.3	51.5	Bdl
68	86.8	339.4	180.3	158.0	62.4	Bdl
71	77.2	352.5	183.9	164.9	105.1	Bdl
Mean	96.3	427.6	141.7	147.9	71.8	Bdl
SD	14.4	166.5	36.8	31.6	14.3	Bdl
Max	135.1	889.9	183.9	200.5	105.1	Bdl
Min	77.2	240.1	66.8	93.6	51.5	Bdl
Median	92.7	409.2	145.9	158.7	71.7	Bdl

*Bdl – below detectable limit

The range of concentration values for heavy metals recorded on the site of the field trial cannot be deemed to be untypical of such sites. Given the lack of uniformity of materials used to cap the site (being derived from three separate sources) and the varying processes that occurred on the site prior to the closure of the steelworks, a heterogeneous growing medium would be expected.

3.2 Plant Growth Data

3.2.1 The Hallside Field Trial – Data from the Treatment Plots

Data assessing the growth parameters of individual clones under each treatment were collected throughout the three year field trial. Parameters measured included survival rates, heights, diameters at half height, number of shoots from each stool and the yields attained according to each silvicultural treatment superimposed on each plot. The results for each parameter measured gave varying results and are initially presented individually. All results were measured for replicate blocks of treatments; the data presented below represents a mean of the results obtained over the three replicate blocks.

Difficulties are noted with the data presented particularly where the survival rate is low. In some instances field data gathered may have been measured from one surviving stool only, particularly for those plots that received no herbicide but with the addition of fertiliser.

To facilitate an understanding of the silvicultural treatments imposed upon individual plots, Figure 3.1 provides details of the labelling used for all histograms within this thesis.

Key to Treatments Used in Figures

All Figures which compare growth data against treatments superimposed on the plots should be read from the bottom up i.e. the first Treatment on the x axis of figure 3.2.1 should be read as 0 0 1 1.

The first number in all cases refers to the use of fertiliser –
Fertiliser Added = 1
No Fertiliser Added = 0

The second number in all cases refers to the use of herbicide –
Herbicide Used = 1
No Herbicide Used = 0

The third number in all cases refers to the planting density of the willow
1 m Density = 1
0.5 m Density = 2

The fourth number in all cases refers to year of first coppice or rotation length.
Coppiced in Year 1 = 1
Coppiced in Year 2 = 2
Coppiced in Year 3 = 3

Consequently treatment 0 0 1 1 may be read as having received no fertiliser, no herbicide, planted at 1m centres and coppiced after 1 years growth.

Figure 3.1 Key to Silvicultural Treatments used in Histograms

(i) Survival Rates

At the end of each growing season the number of clones surviving for each treatment plot were manually counted and recorded against the treatments received by the individual plots. All results were recorded as percentages and are reproduced in full in Annex 1. Difficulties were experienced in recording the survival of the willow due to either weeds hiding the stools in the first year or difficulties at plot edges in determining the exact plot boundaries.

Plots were initially pegged to provide an indication of the boundary however with hindsight each individual plot should also have been taped/ marked to avoid error at the boundaries and what is suspected to be double recording. The main consequence of this action has been that survival rates in some instances appear to increase over the three year period. As no additional planting was undertaken to replace dead stools this would not have been possible. Survival results in the final year are considered to be the most accurate of all survival rates recorded, as it was easier to identify the surviving stools by their size and shoots where previously coppiced. Figures 3.2.1 to 3.2.5 provide an overview of the survival rates for each individual clone on a yearly basis against silvicultural treatments. Figure 3.2.6 gives an overview of survival rates for all clones against silvicultural treatments in year 3 only i.e. the final year.

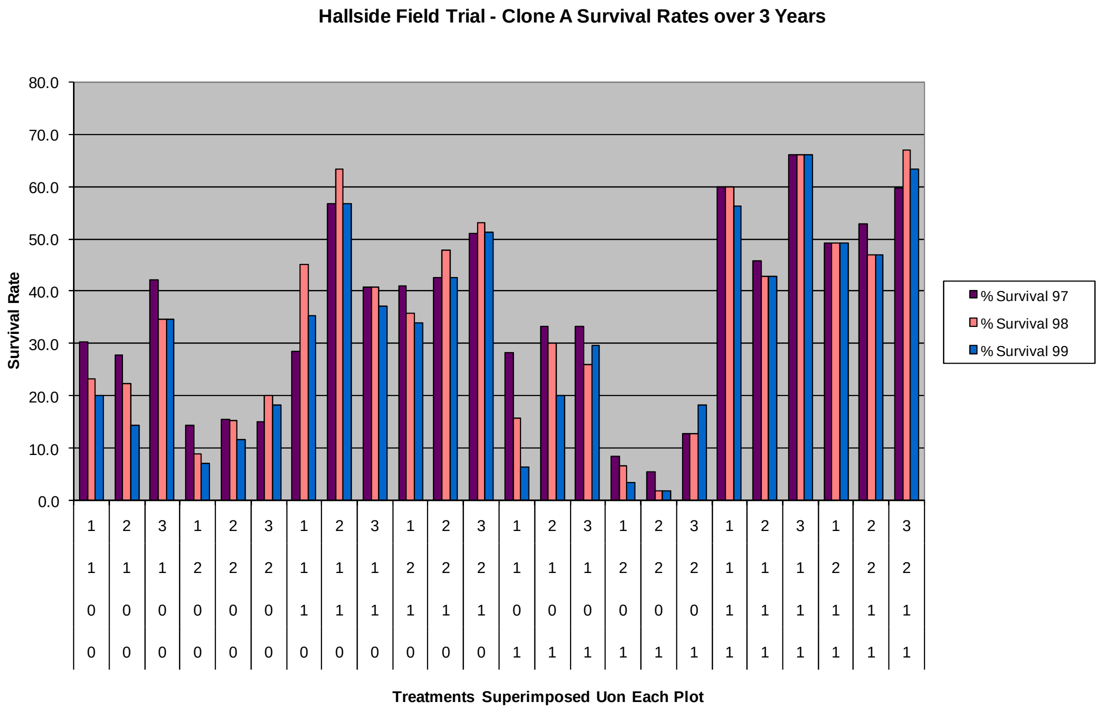


Figure 3.2.1 Hallside Field Trial – Clone A Survival Rates For 3 Years Against Silvicultural Treatments

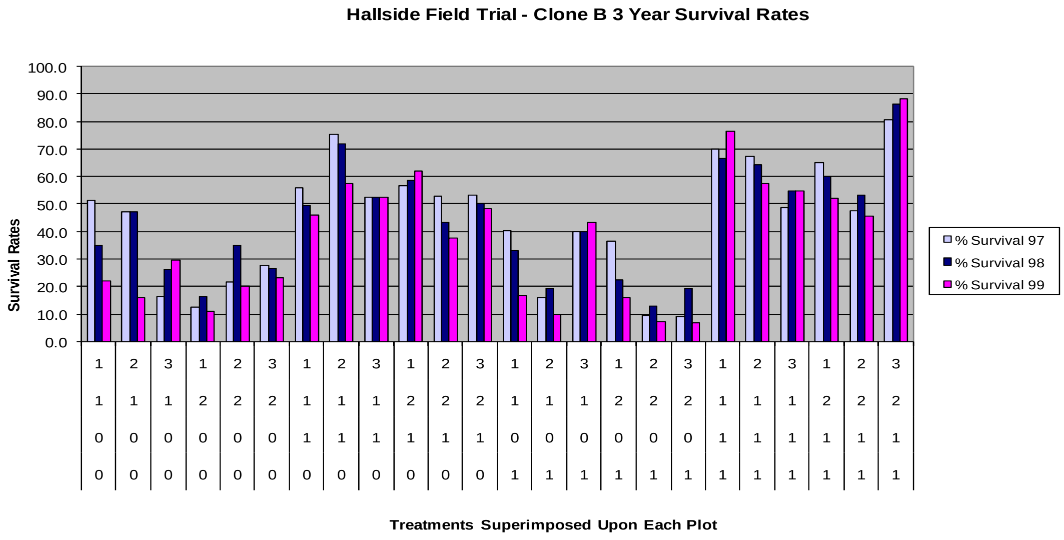


Figure 3.2.2 Hallside Field Trial – Clone B Survival Rates For 3 Years Against Silvicultural Treatments

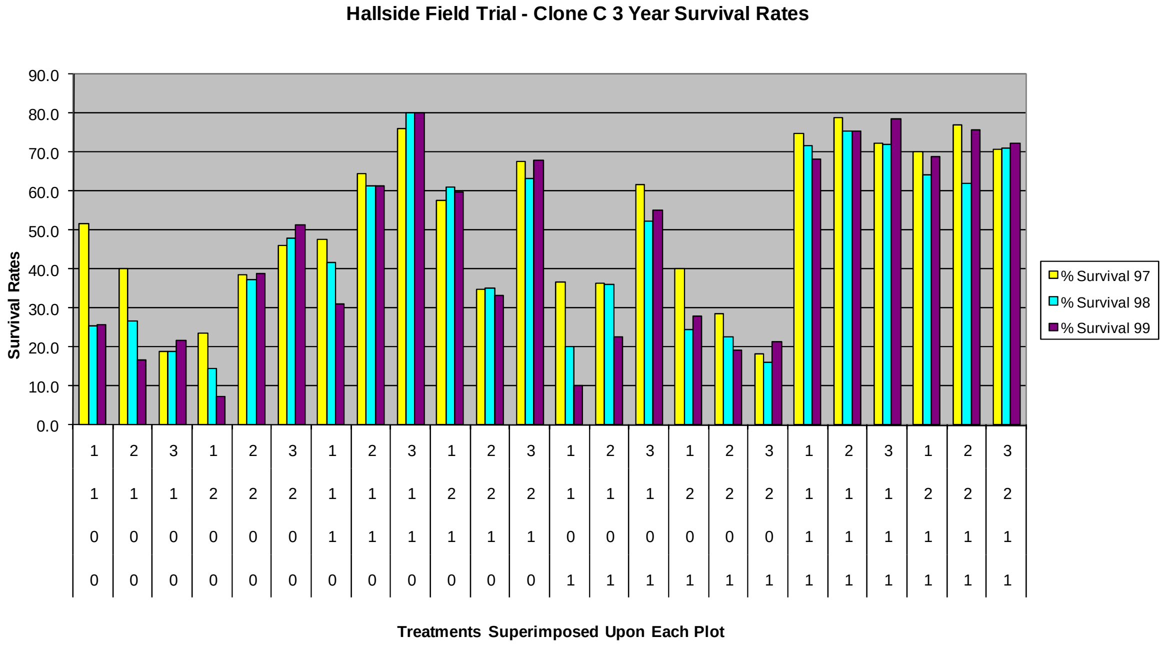


Figure 3.2.3 Hallside Field Trial – Clone C Survival Rates For 3 Years Against Treatments

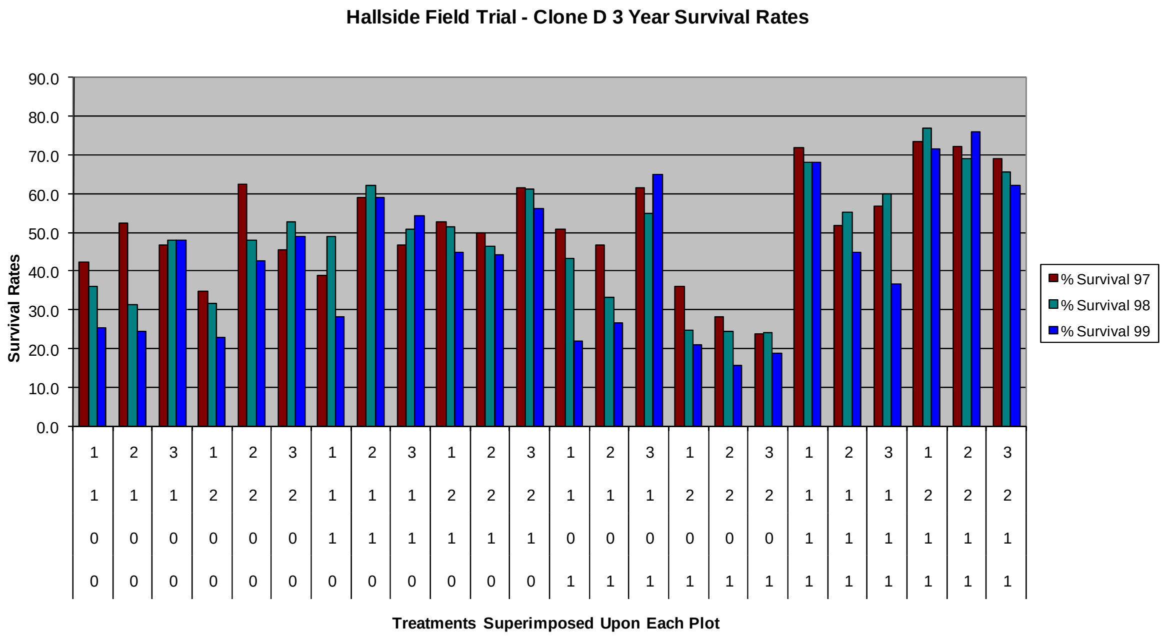


Figure 3.2.4 Hallside Field Trial – Clone D Survival Rates For 3 Years Against Treatments

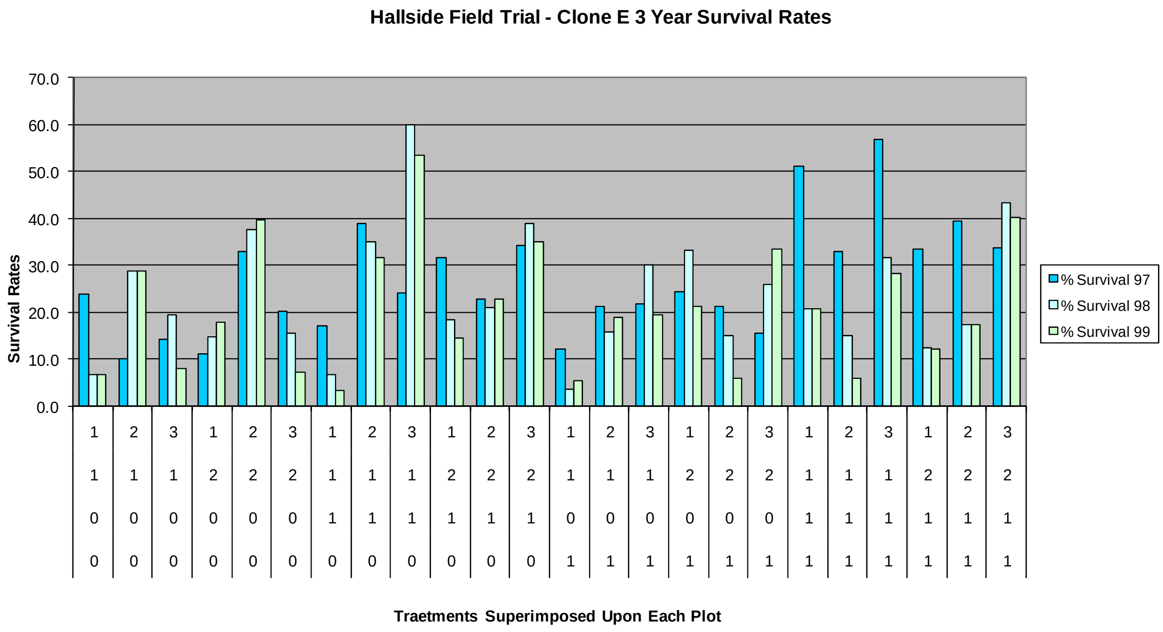


Figure 3.2.5 Hallside Field Trial – Clone E Survival Rates For 3 Years Against Treatments

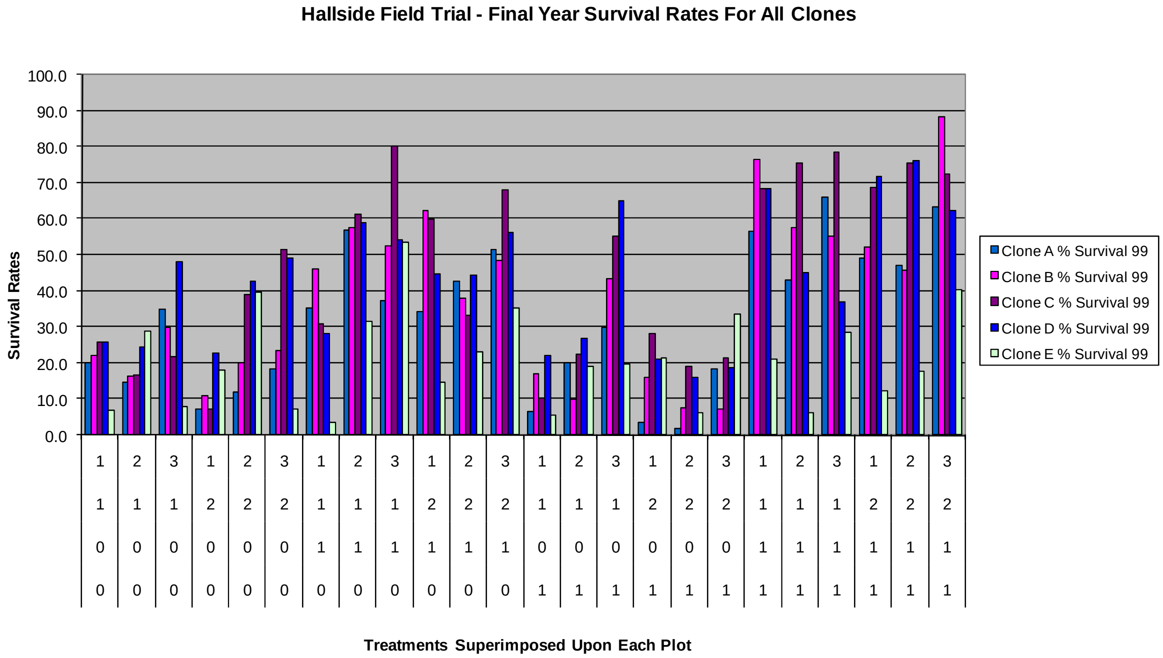


Figure 3.2.6 Hallside Field Trial – All Clones Survival Rates For Year 3 Against all Treatments

(ii) Heights

To ascertain whether the treatments had any effects upon the growth rates of the five clones of willow planted in each plot, measurements were manually recorded of the heights attained by a maximum of five surviving stools. The height values presented represent the mean value for the length of all shoots observed and recorded from the surviving stool. As the height values represent stools of varying age, dependant upon year of coppicing, all height results were taken annually. The full table of results is reproduced in Annex 1. All results are recorded in cms.

Figures 3.2.7 –3.2.11 display the results obtained for each individual clone illustrating the effects that the varying silvicultural treatments had upon clone heights. Figure 3.2.12 is a collective histogram for year 3 results only.

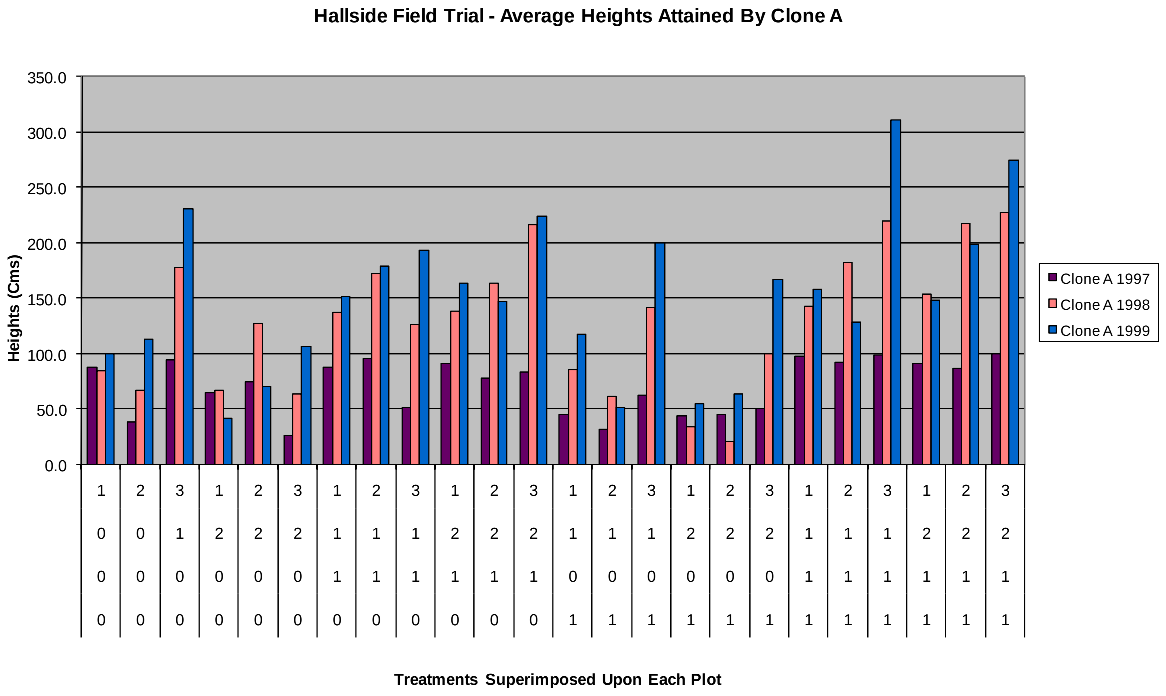


Figure 3.2.7 Hallside Field Trial – Clone A Average Height Recorded For 3 Years Against Treatments

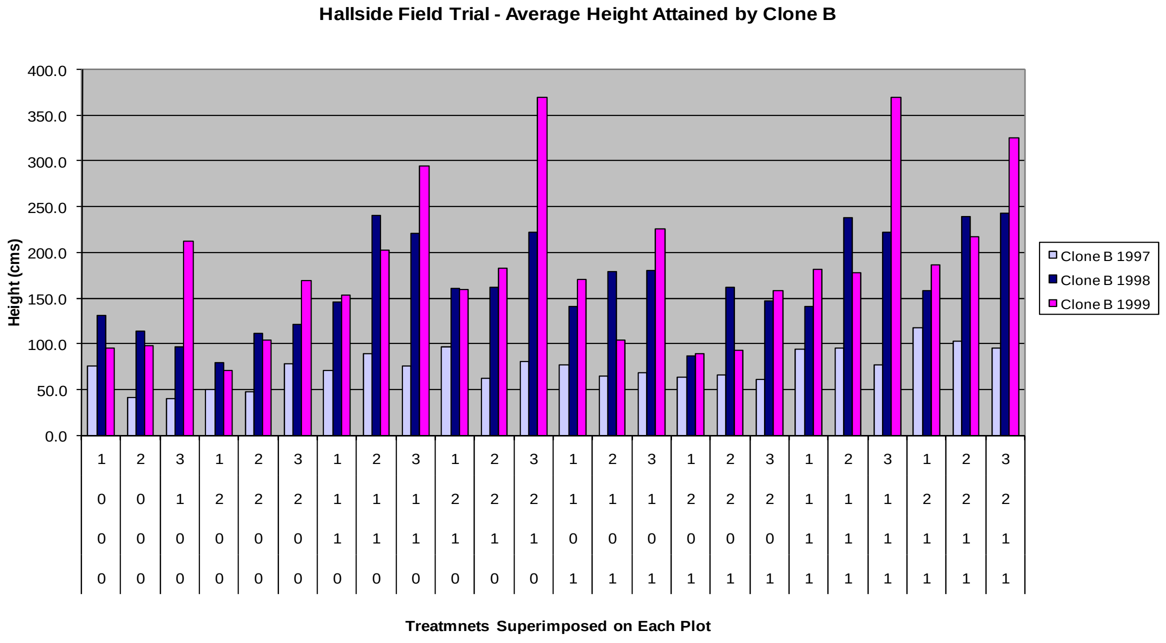


Figure 3.2.8 Hallside Field Trial –Clone B Average Height Recorded For 3 Years Against Treatments

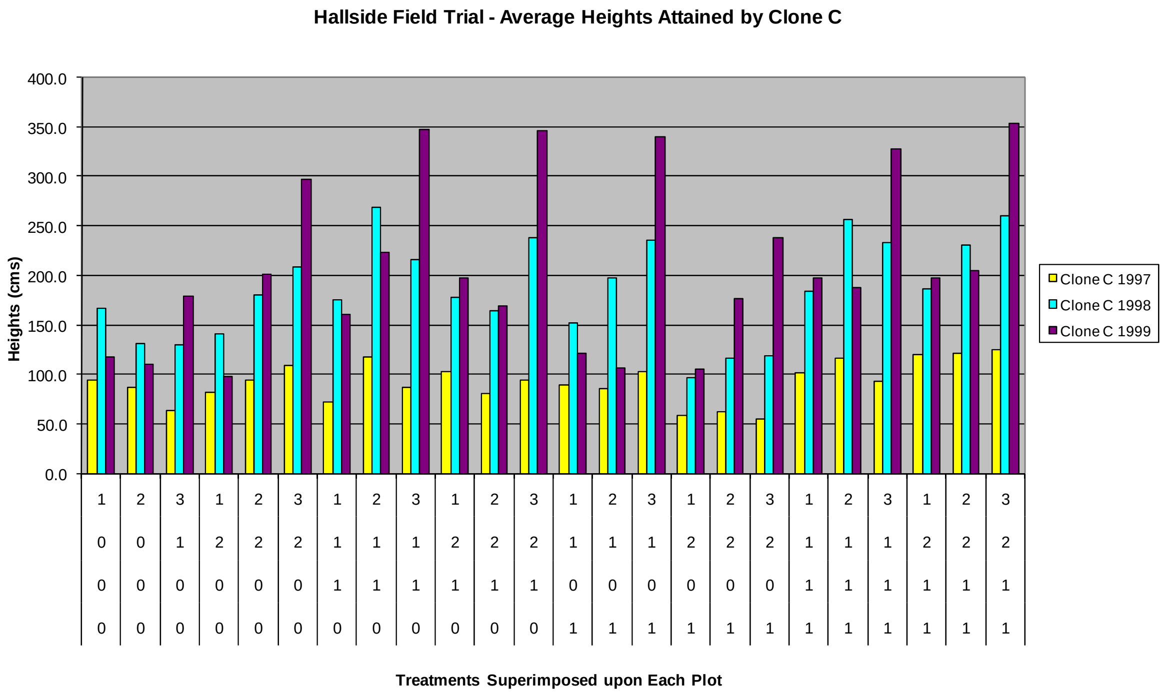


Figure 3.2.9 Hallside Field Trial –Clone C Average Height Recorded For 3 Years Against Treatments

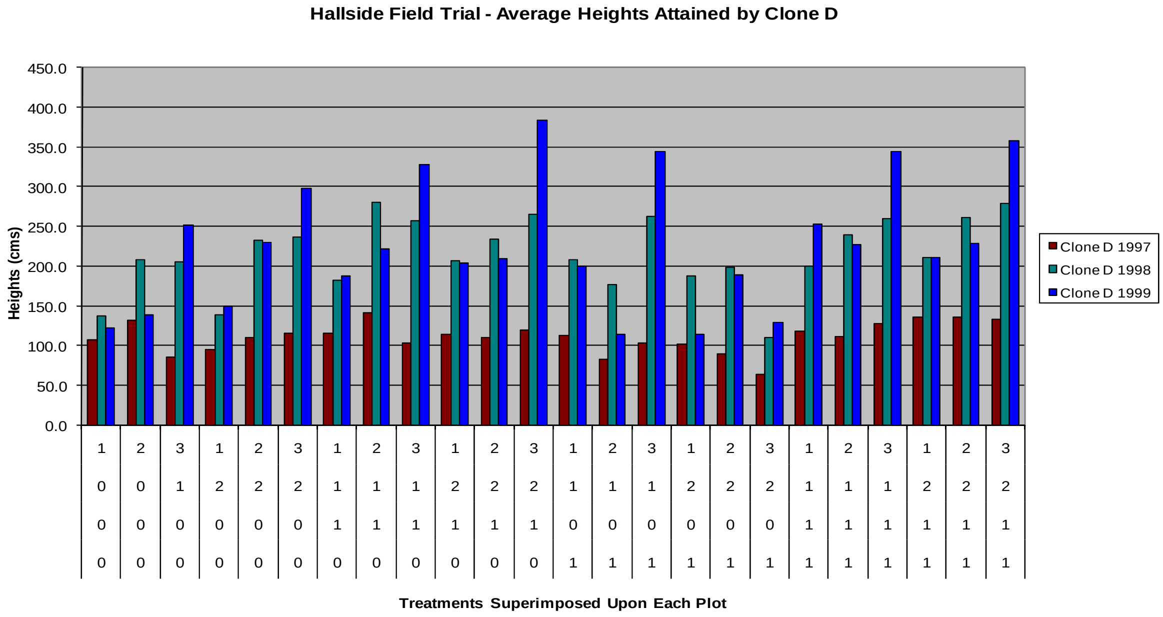


Figure 3.2.10 Hallside Field Trial –Clone D Average Height Recorded For 3 Years Against Treatments

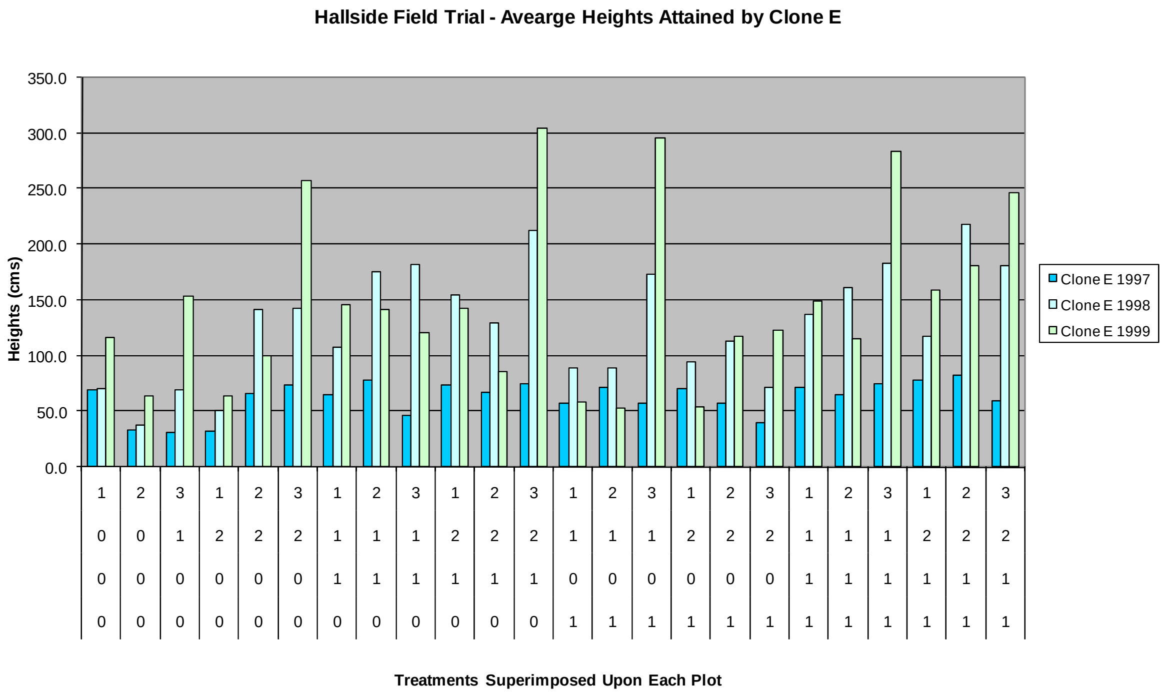


Figure 3.2.11 Hallside Field Trial –Clone E Average Height Recorded For 3 Years Against Treatments

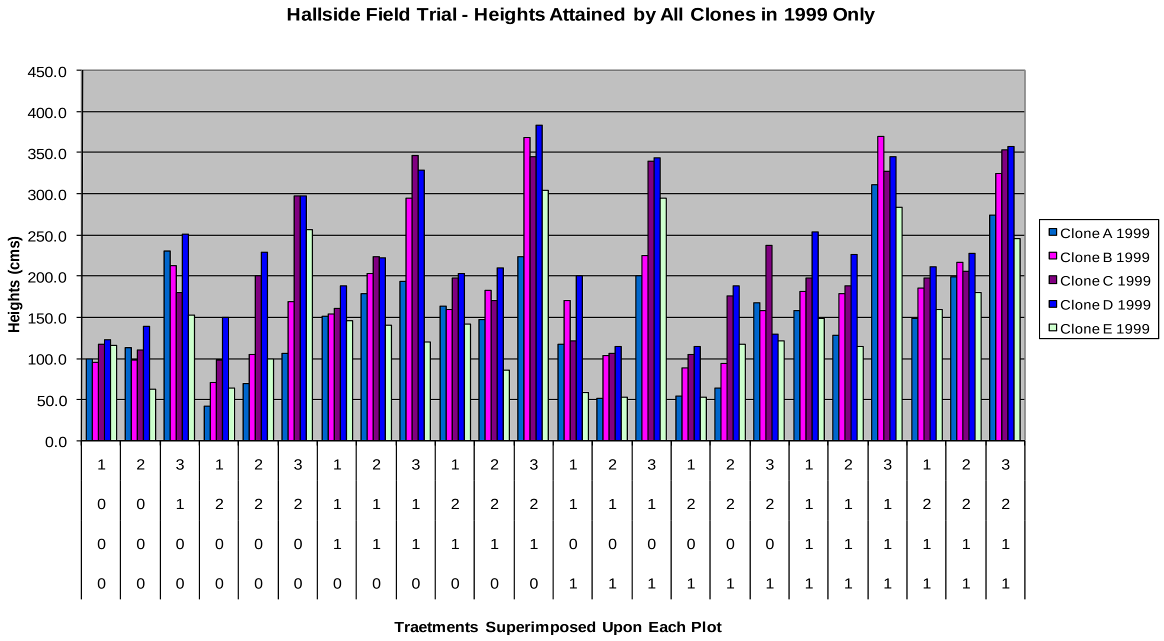


Figure 3.2.12 Hallside Field Trial –All Clones Average Height Recorded For Year 3 Against Treatments

(iii) Diameters

As with heights, diameters at half height were recorded using Camlab Digimax TXP 2001 electronic callipers. These results are reproduced in Figures 3.2.13-3.2.17 for each individual clone with Figure 3.2.18 representing the combined values for all clones in the final year of the trial. Again, due to the volume of data collected, all results have been expressed as mean for the results within the plots. The full table of raw data is reproduced in Annex 1. All results are recorded in mm.

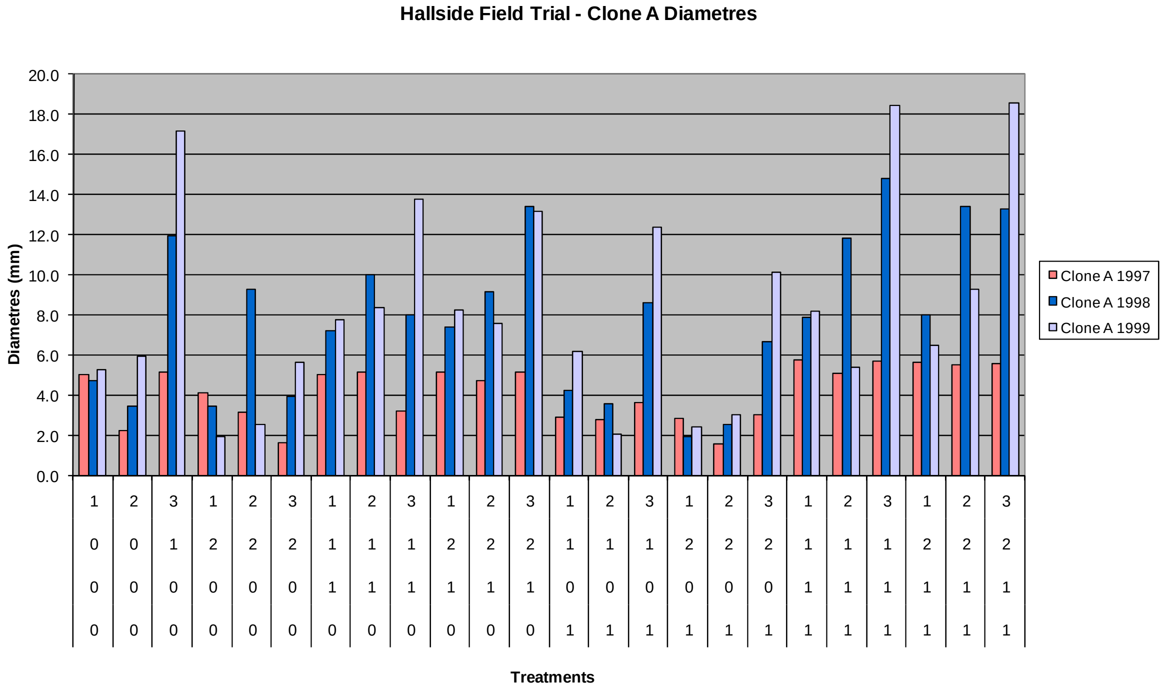


Figure 3.2.13 Hallside Field Trial –Clone A Average Diameters Recorded For 3 Years Against Treatments

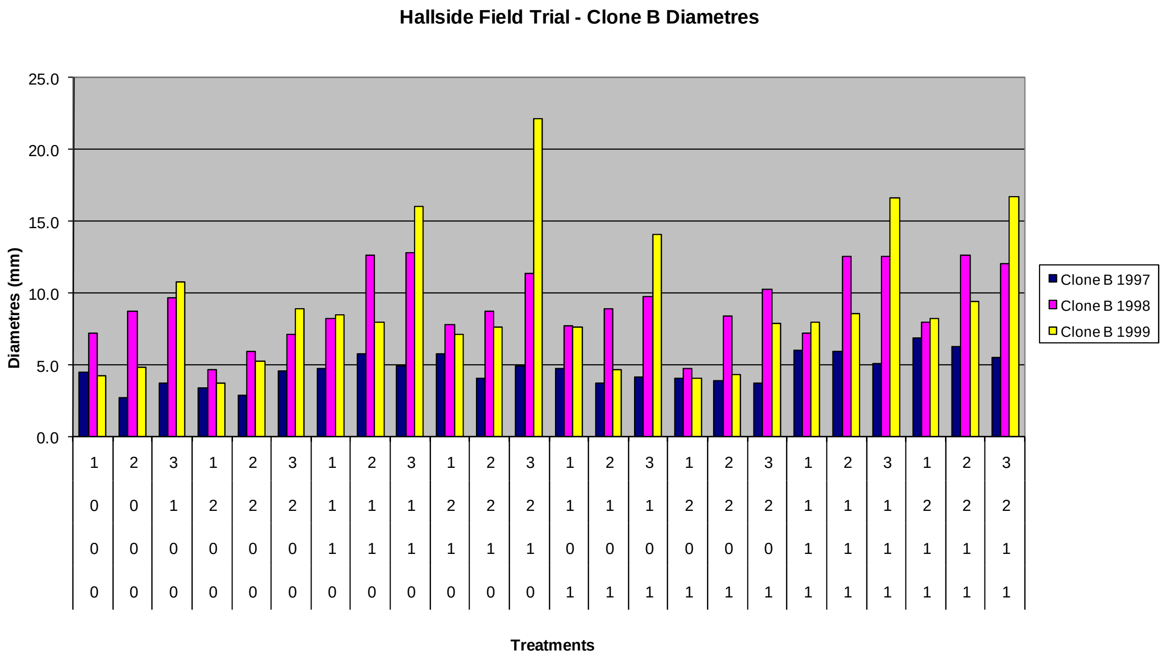


Figure 3.2.14 Hallside Field Trial –Clone B Average Diameters Recorded For 3 Years Against Treatments

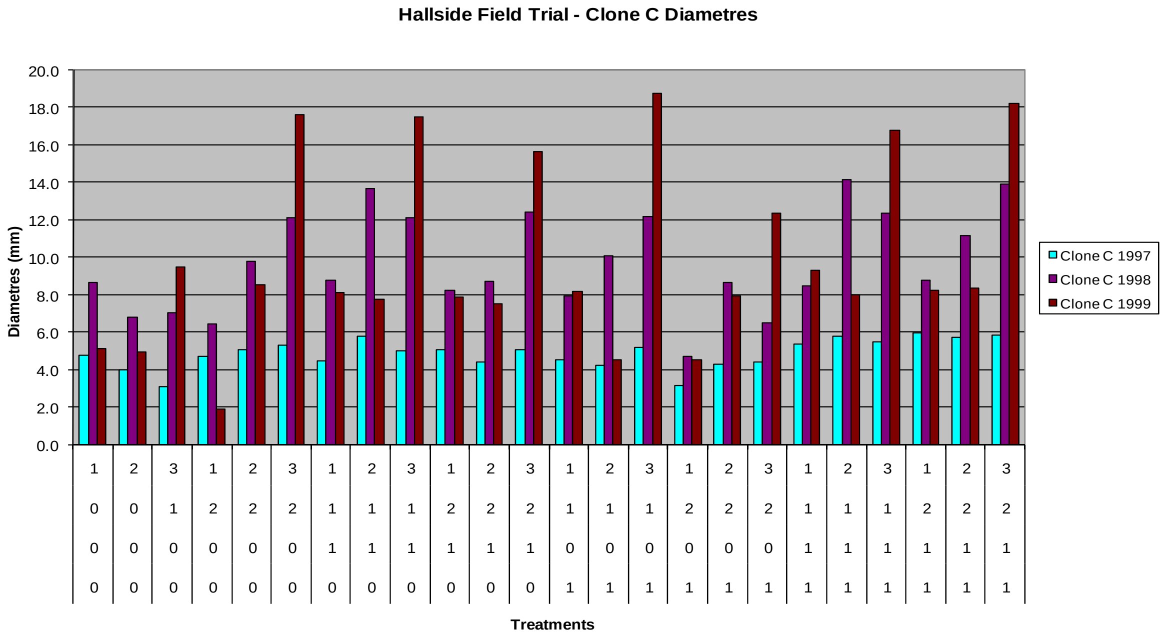


Figure 3.2.15 Hallside Field Trial –Clone C Average Diameters Recorded For 3 Years Against Treatments

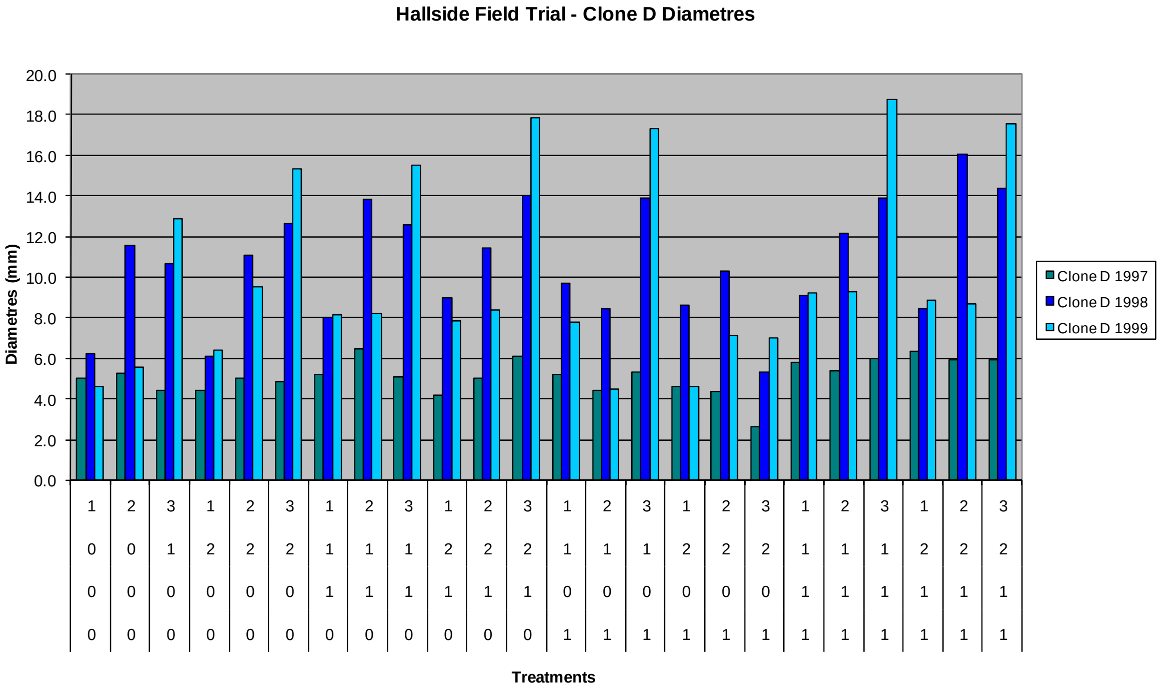


Figure 3.2.16 Hallside Field Trial –Clone D Average Diameters Recorded For 3 Years Against Treatments

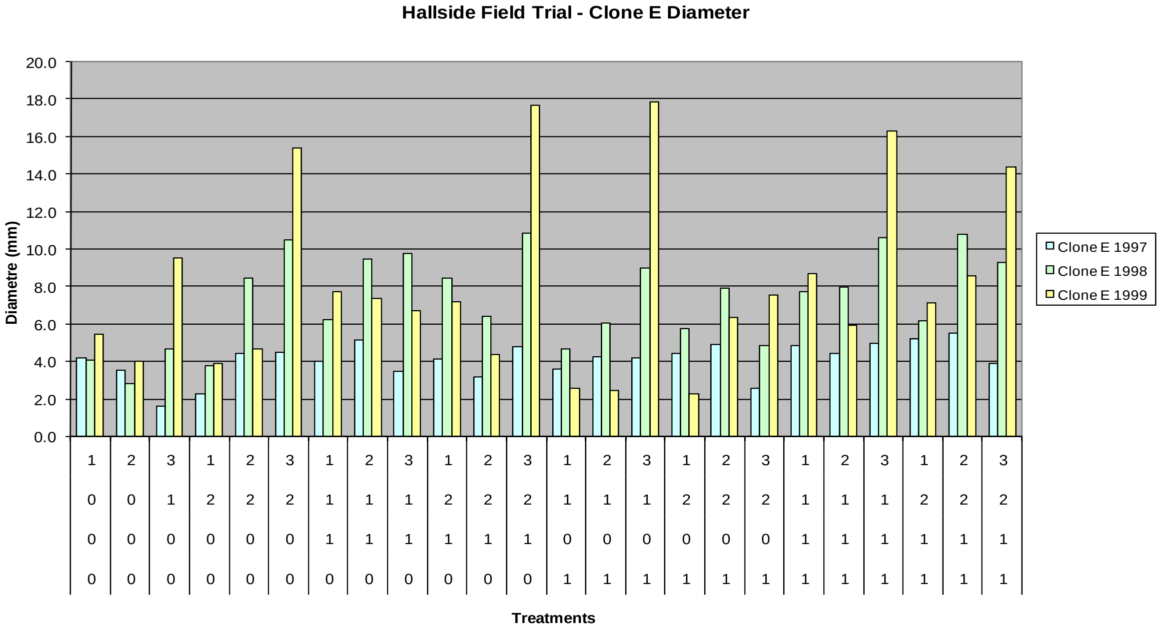


Figure 3.2.17 Hallside Field Trial –Clone E Average Diameters Recorded For 3 Years Against Treatments

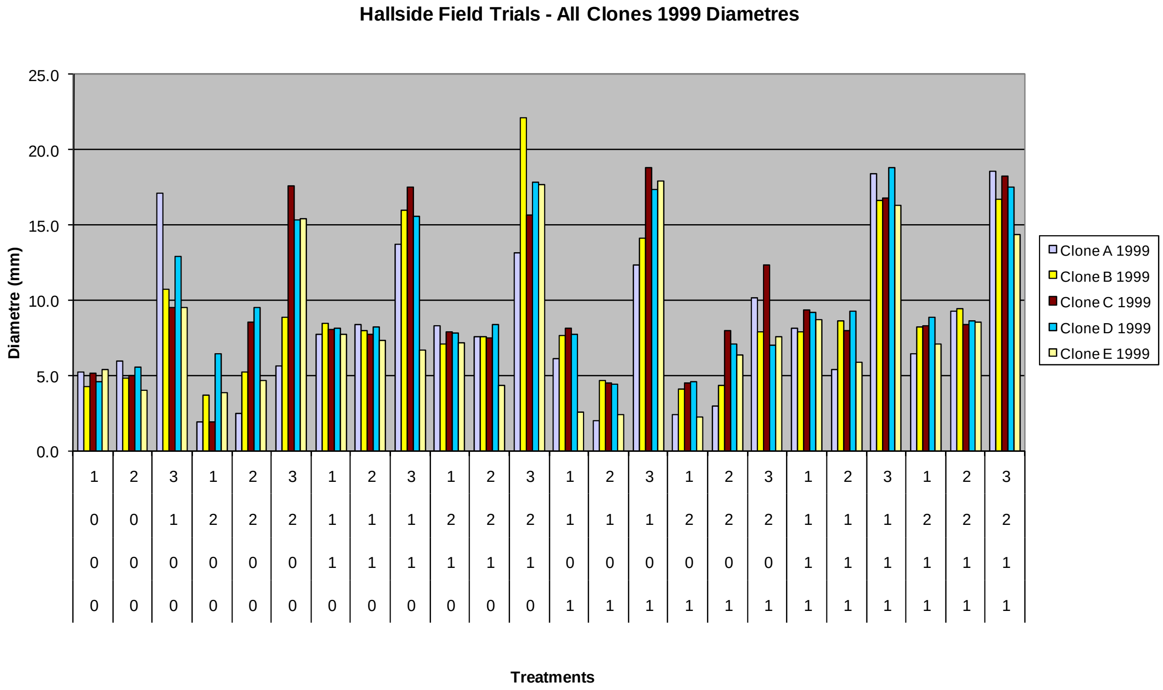


Figure 3.2.18 Hallside Field Trial –All Clones Average Diameters Recorded For Year 3 Against Treatments

(iv) Number of Shoots

To assess the effect of coppicing in encouraging increased biomass production, (and potentially increased metal accumulation) an assessment was made on an annual basis of the number of shoots produced by individual stools. The average results for the data collected are reproduced in full in Annex 1.5. Figures 3.2.19-3.2.24 provide data for individual clones and the combined results for all clones in year 3.

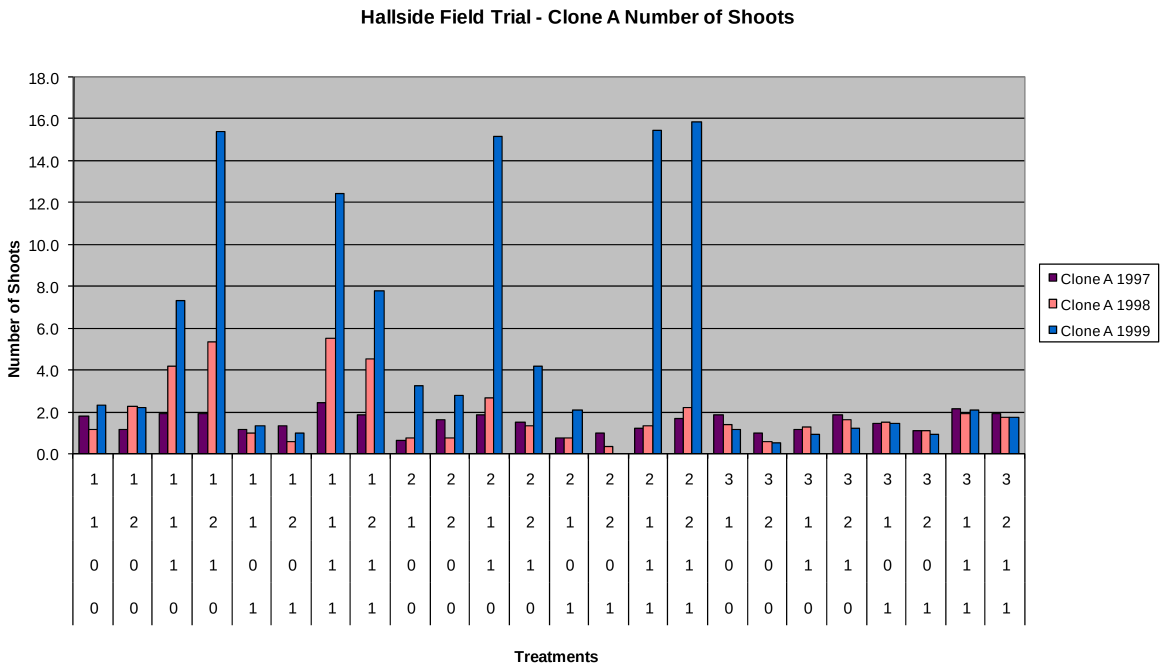


Figure 3.2.19 Hallside Field Trial –Clone A Average Number of Shoots Recorded For 3 Years Against Treatments

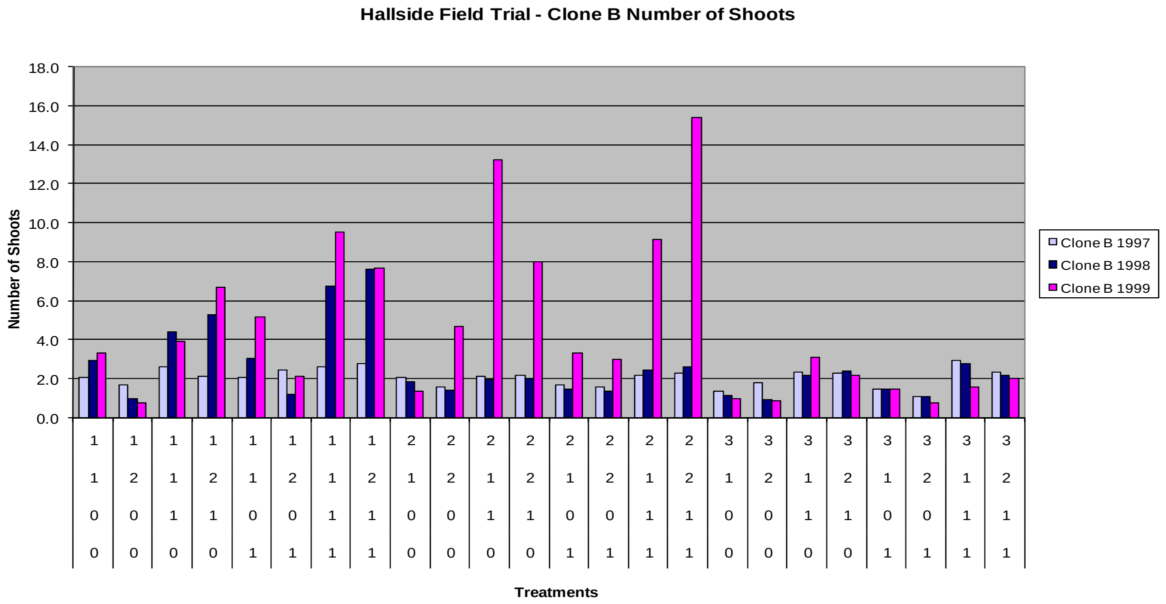


Figure 3.2.20 Hallside Field Trial –Clone B Average Number of Shoots Recorded For 3 Years Against Treatments

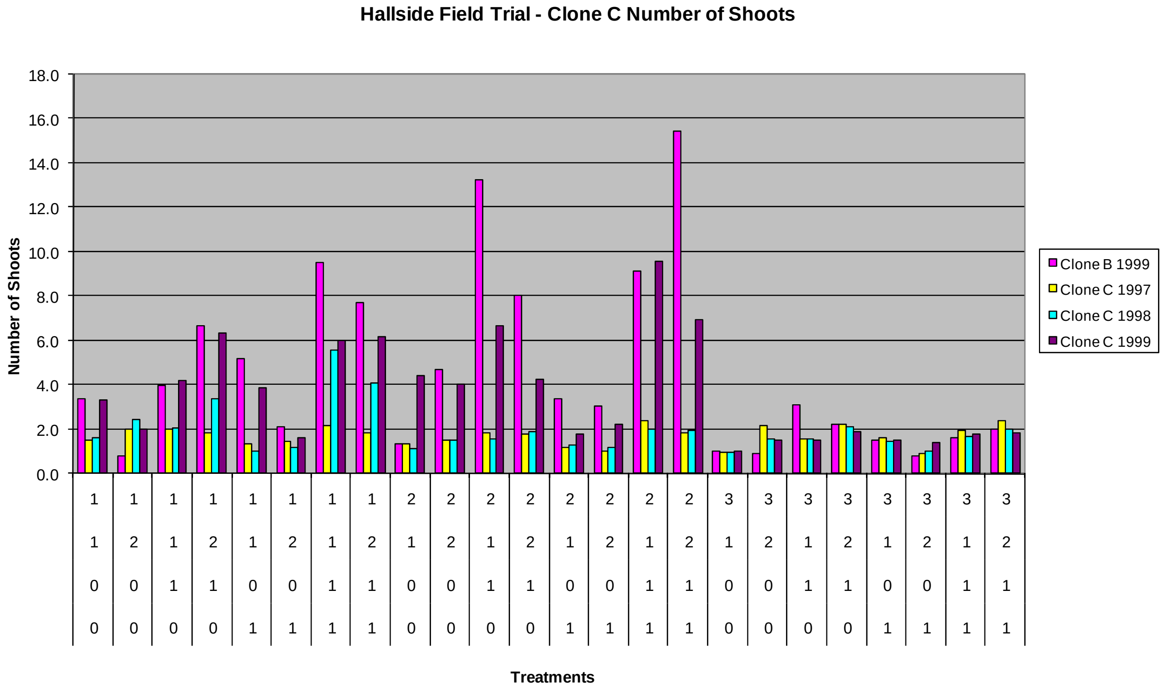


Figure 3.2.21 Hallside Field Trial –Clone C Average Number of Shoots Recorded For 3 Years Against Treatments

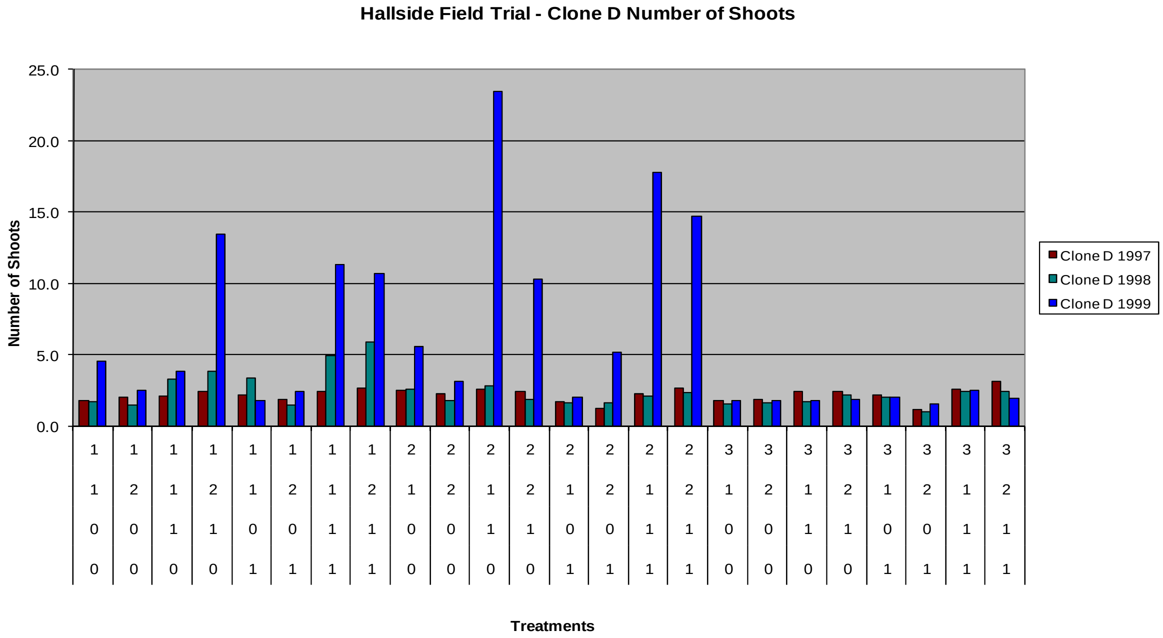


Figure 3.2.22 Hallside Field Trial –Clone D Average Number of Shoots Recorded For 3 Years Against Treatments

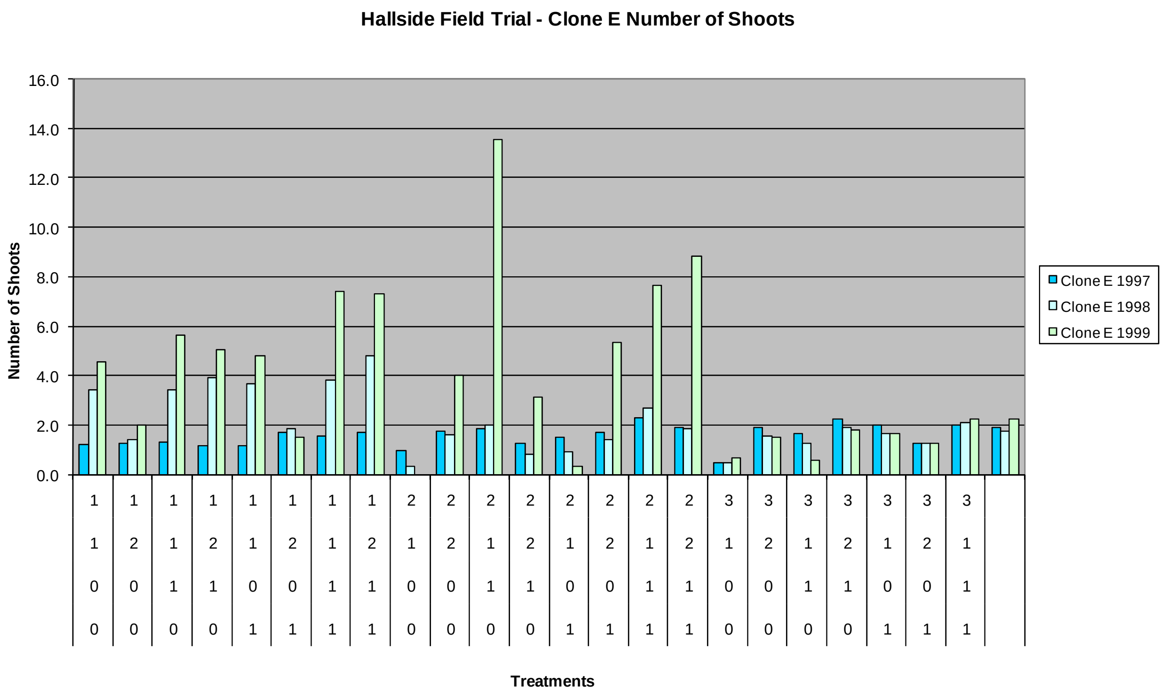


Figure 3.2.23 Hallside Field Trial –Clone E Average Number of Shoots Recorded For 3 Years Against Treatments

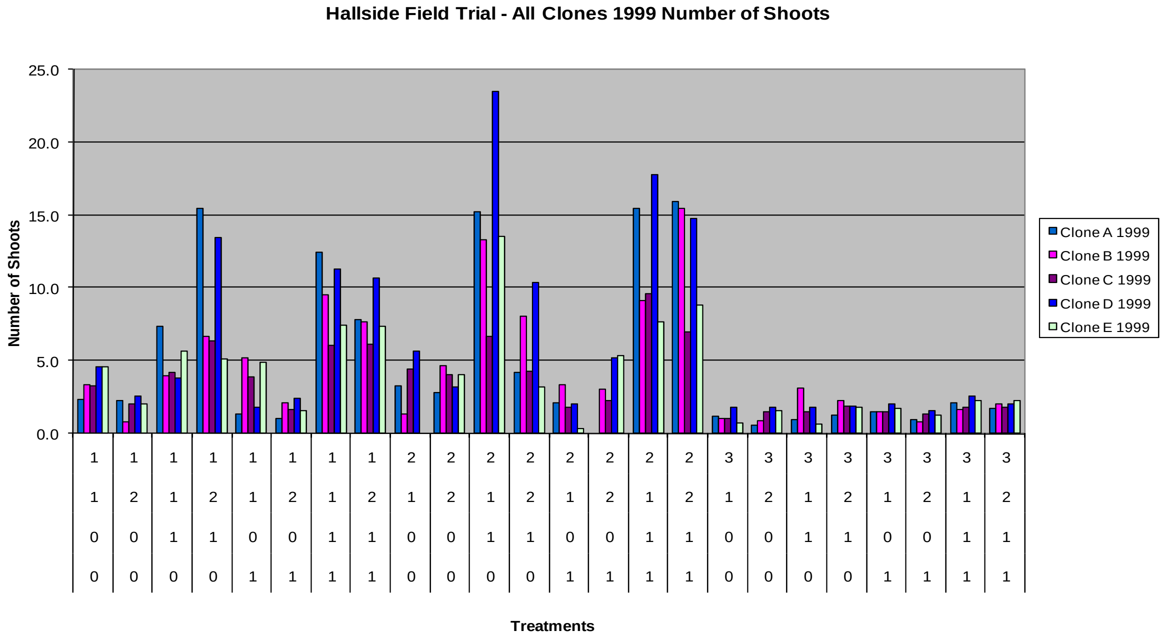


Figure 3.2.24 Hallside Field Trial –All Clones Average Number of Shoots Recorded For Year 3 Only Against Treatments

(v) Yields

On an annual basis, dependent upon the rotation length of the willow coppice, yield assessments were made for each individual clone against treatment. All stools to be harvested were cut using hand held loppers and weighed in the field (or if too small returned to the laboratory for weighing on smaller weighing apparatus).

Due to variations in the moisture content of all field plants, to determine the accurate dry weight of yields, samples were oven dried to determine the moisture content. Determination of the moisture content for each individual sample allowed field yields to be converted to their dry weight equivalents. All results are expressed in oven dry tonnes per hectare per annum. Plot yields have been multiplied so that all results are expressed as a per hectare value. Similarly, where more than 1 years worth of yield was collected these have been divided by the appropriate value to give an annual yield. These results are produced in the figures below. The full tables of yield data are reproduced in Annex A1.

A. Hallside Field Trial – Year 1 Yields Obtained from all Plots subject to 1 Rotation Length

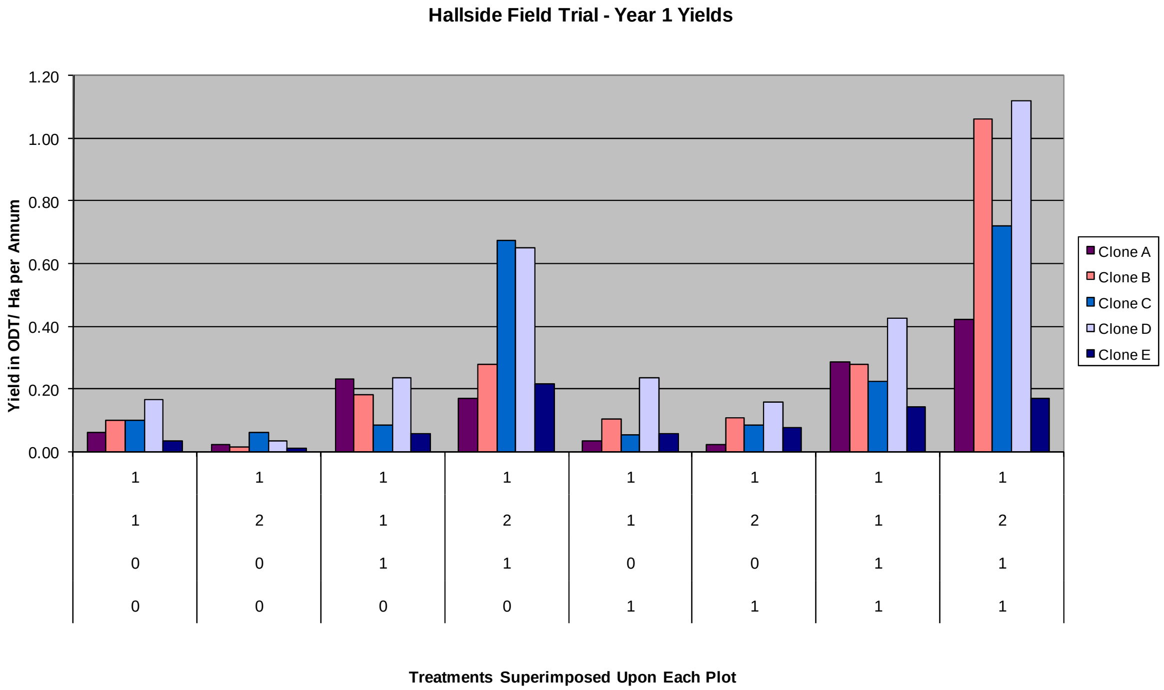


Figure 3.2.25 Hallside Field Trial –Year 1 Average Yields Against Treatments For all Clones

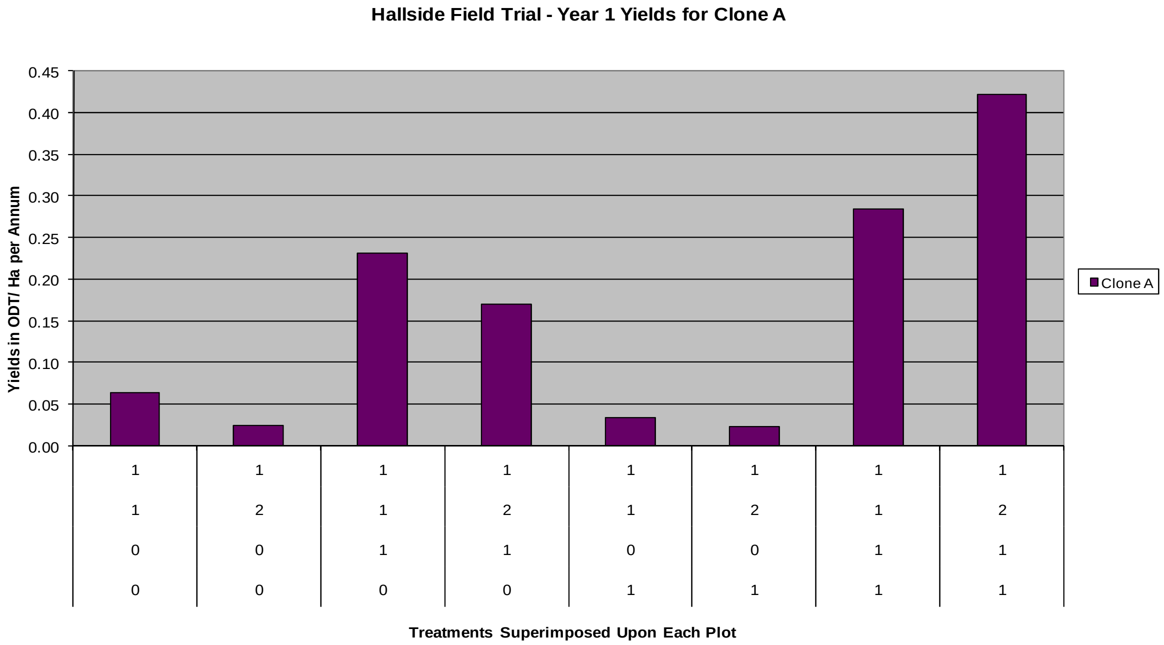


Figure 3.2.26 Hallside Field Trial –Year 1 Average Yields Against Treatments For Clone A

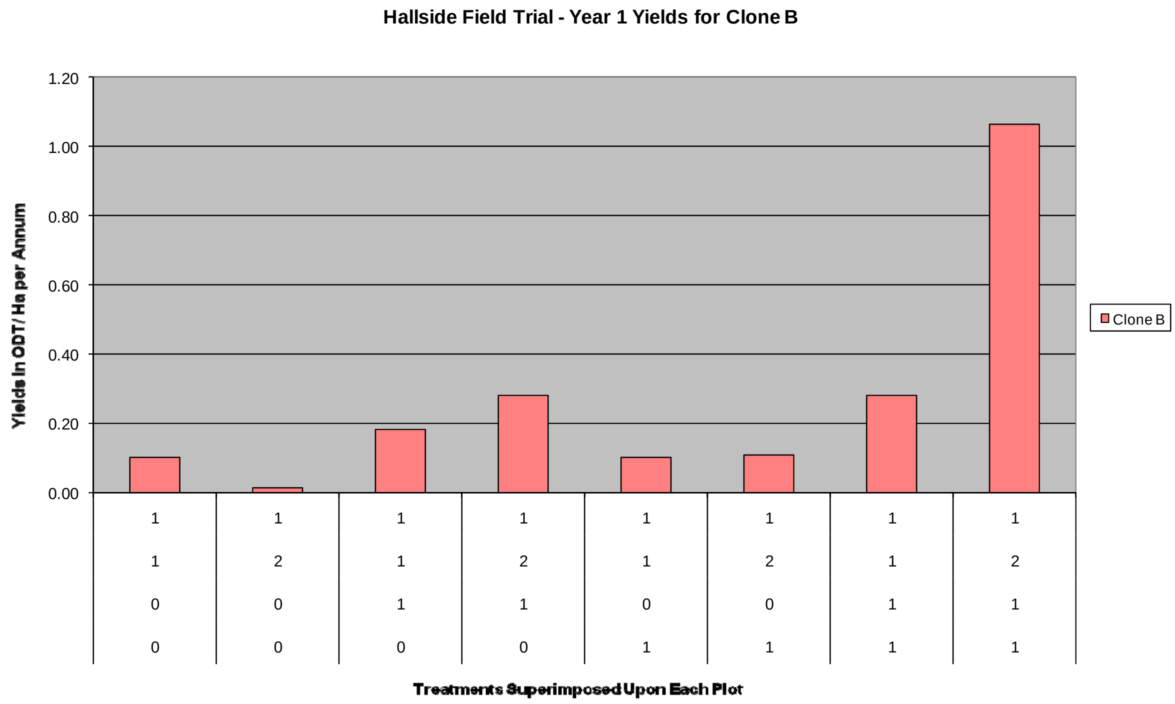


Figure 3.2.27 Hallside Field Trial –Year 1 Average Yields Against Treatments For Clone B

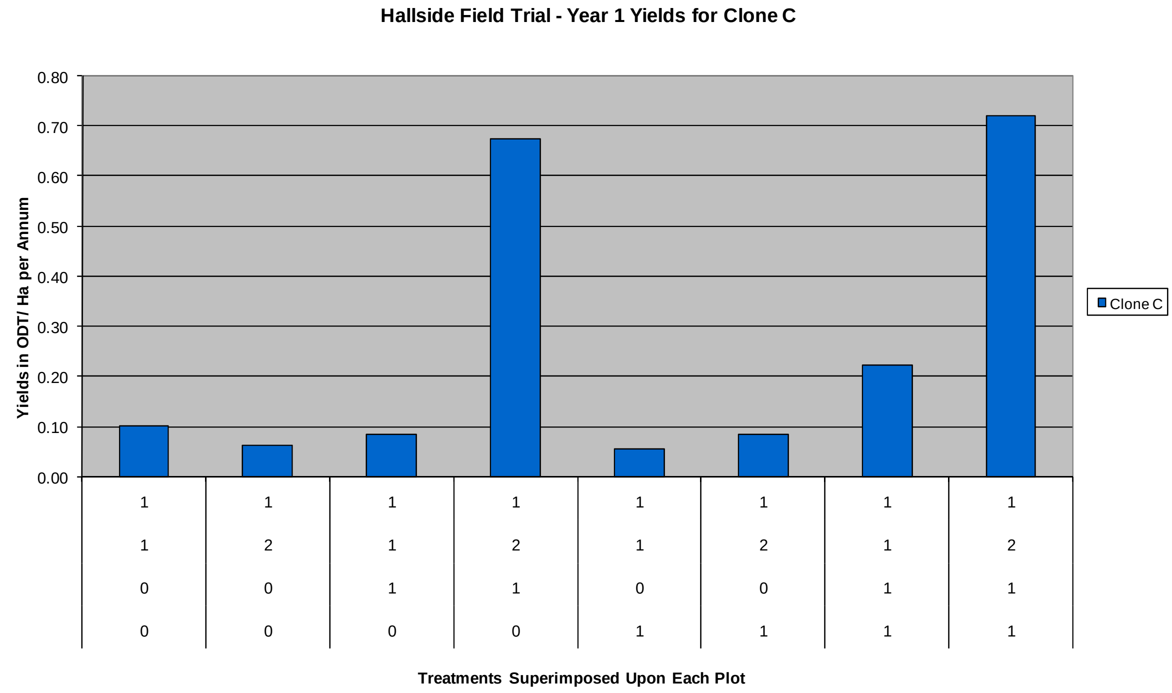


Figure 3.2.28 Hallside Field Trial –Year 1 Average Yields Against Treatments For Clone C

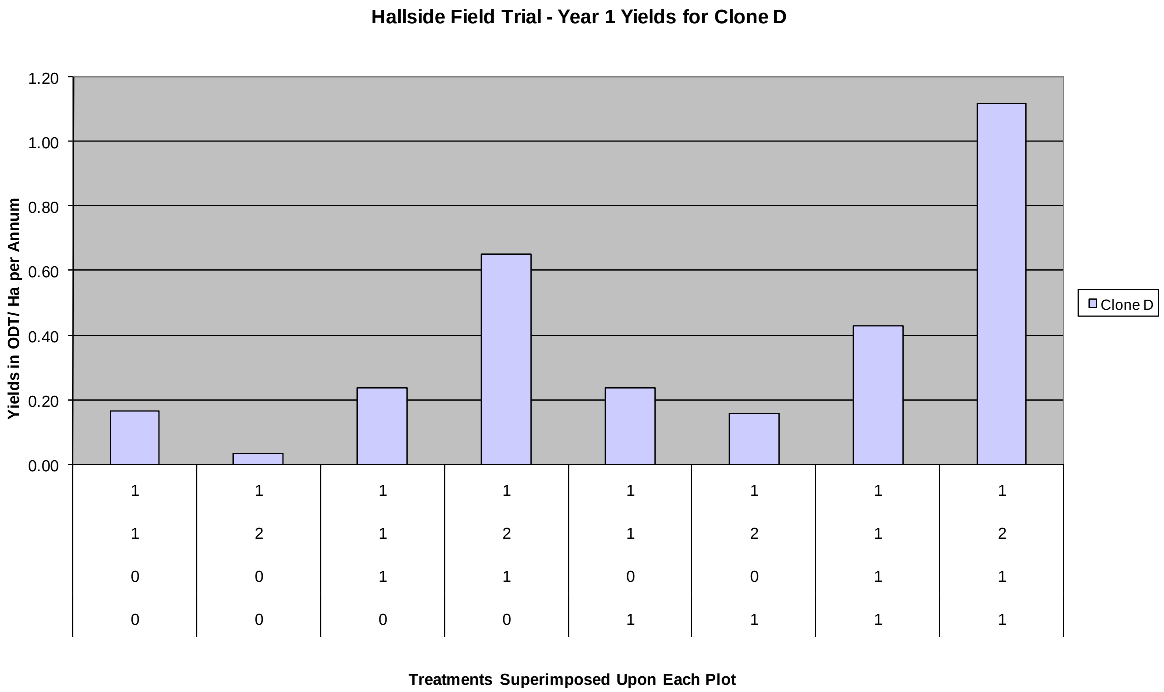


Figure 3.2.29 Hallside Field Trial –Year 1 Average Yields Against Treatments For Clone D

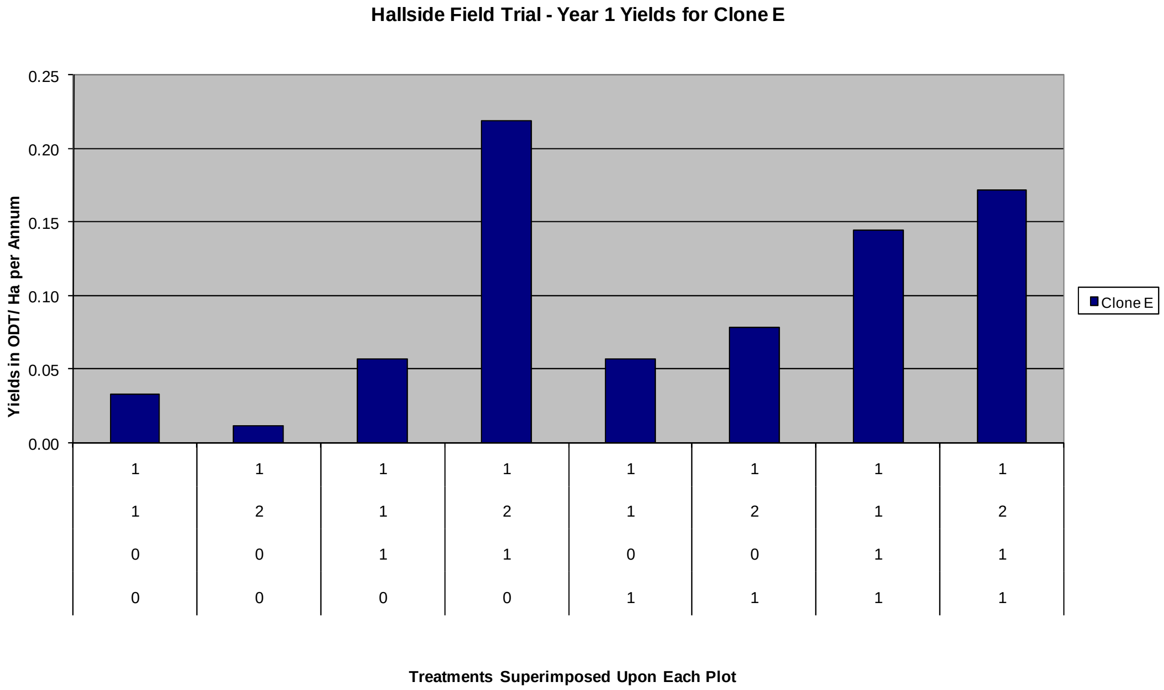


Figure 3.2.30 Hallside Field Trial –Year 1 Average Yields Against Treatments For Clone E

B. Hallside Field Trial – Year 2 Yields Obtained from all Plots subject to 1 or 2 Year Rotation Length

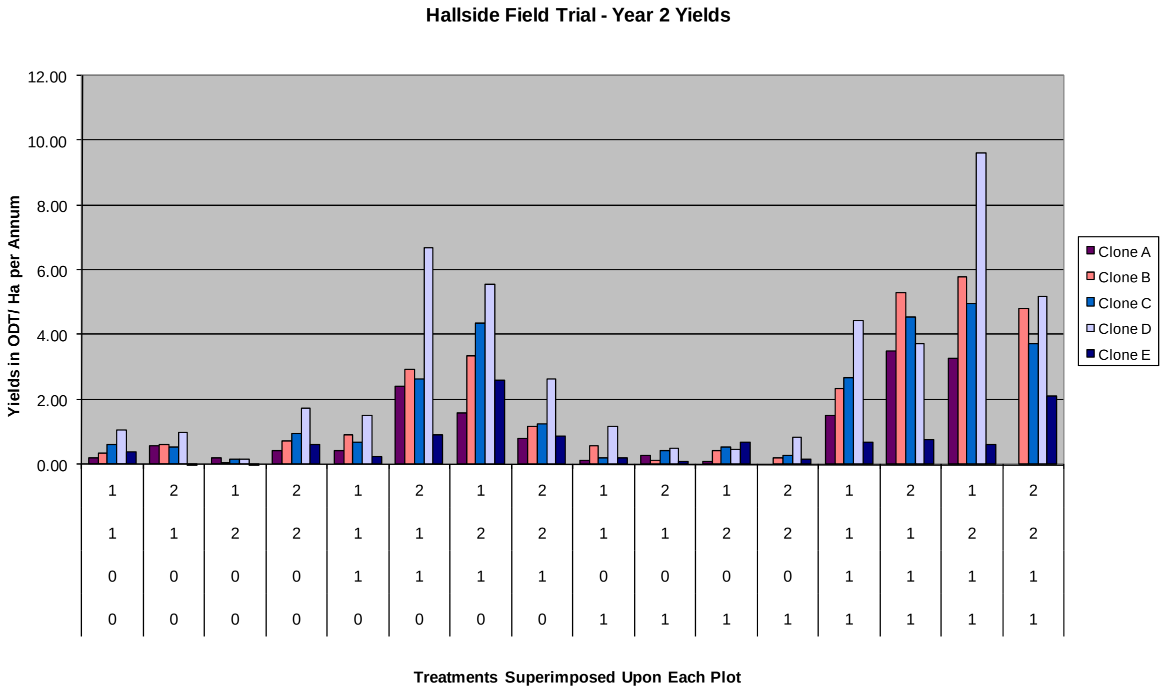


Figure 3.2.31 Hallside Field Trial –Year 2 Average Yields Against Treatments For all Clones

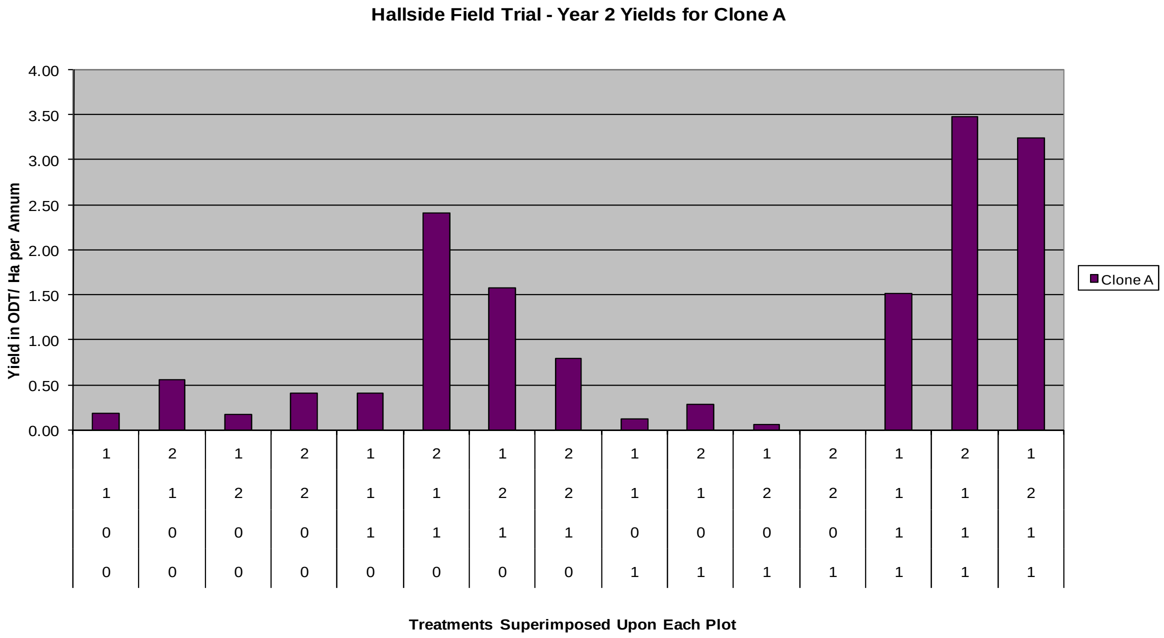


Figure 3.2.32 Hallside Field Trial –Year 2 Average Yields Against Treatments For Clone A

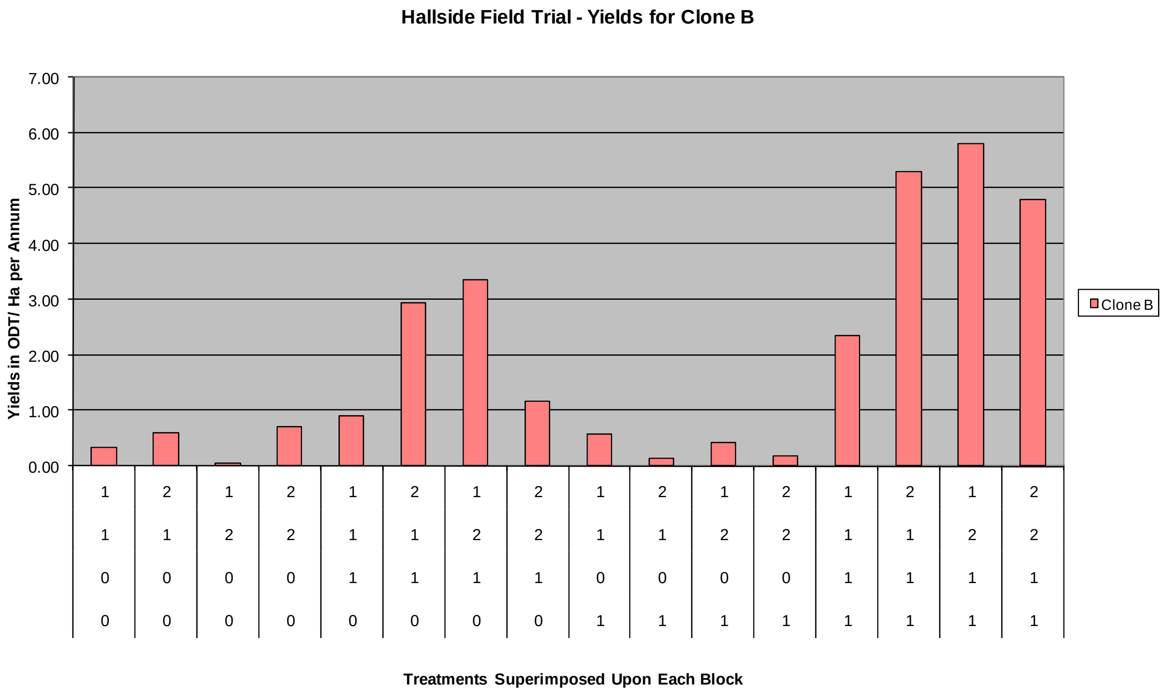


Figure 3.2.33 Hallside Field Trial –Year 2 Average Yields Against Treatments For Clone B

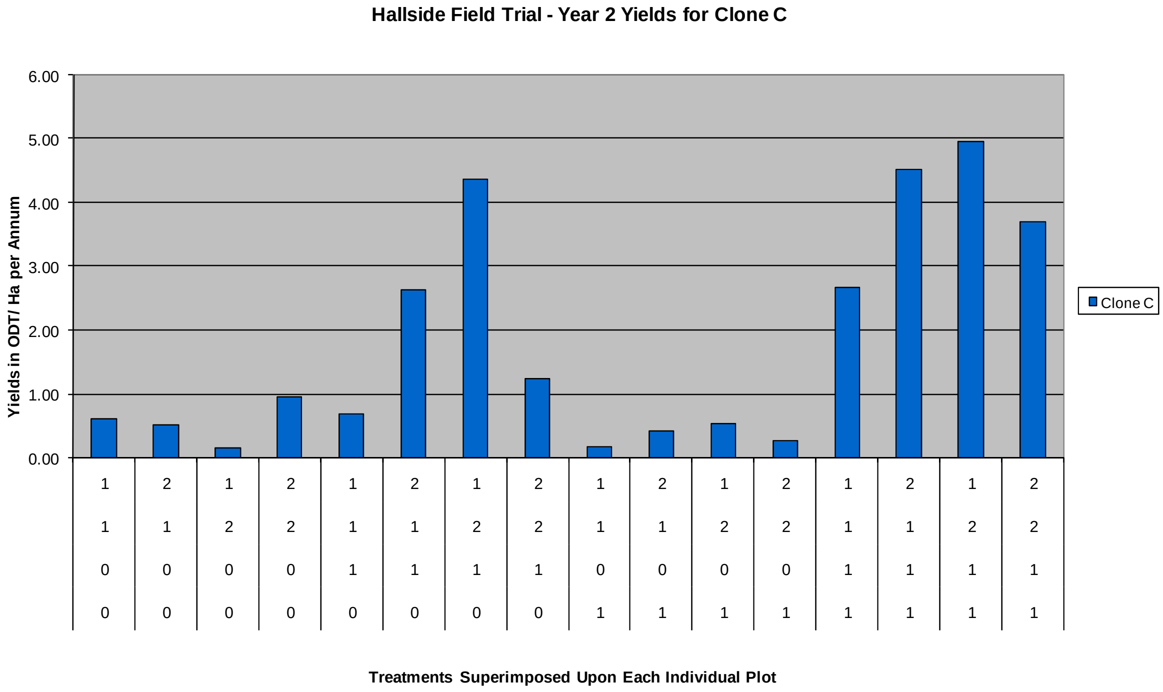


Figure 3.2.34 Hallside Field Trial –Year 2 Average Yields Against Treatments For Clone C

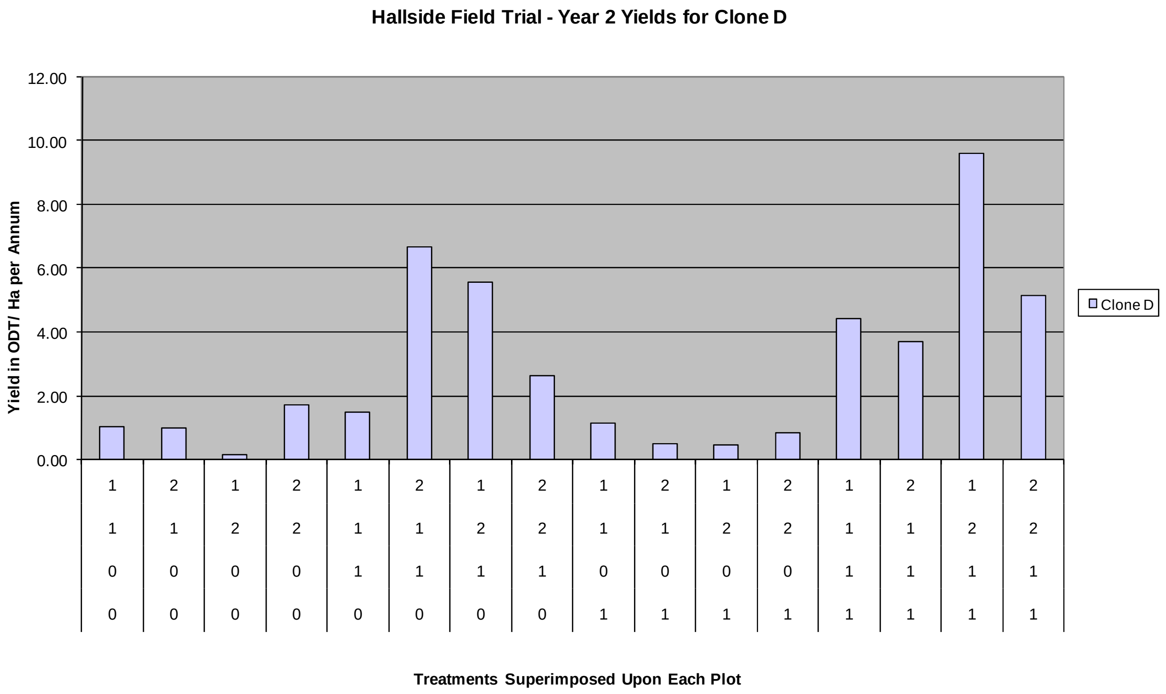


Figure 3.2.35 Hallside Field Trial –Year 2 Average Yields Against Treatments For Clone D

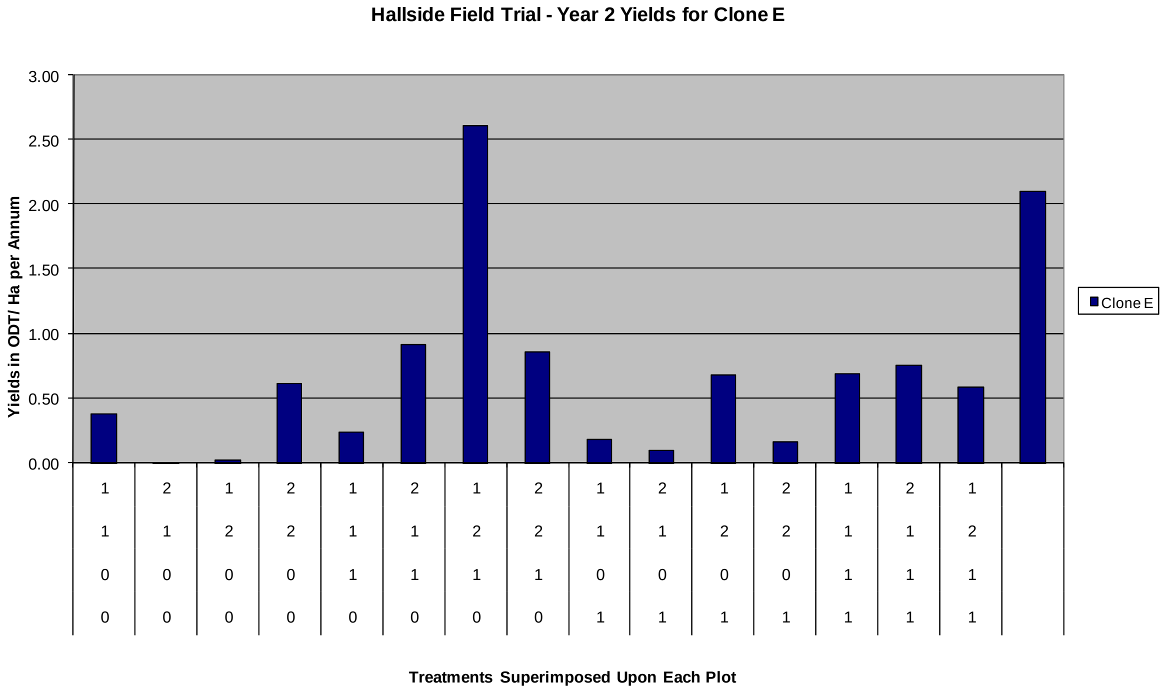


Figure 3.2.36 Hallside Field Trial –Year 2 Average Yields Against Treatments For Clone E

C. Hallside Field Trial – Year 3 Yields Obtained from all Plots

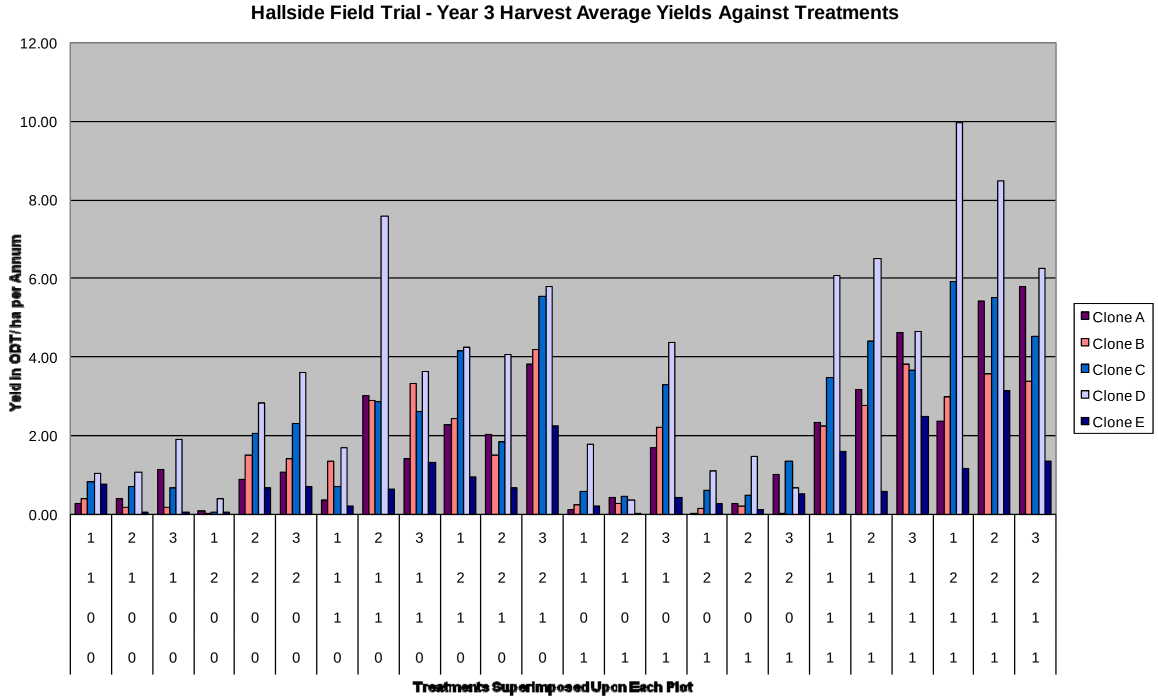


Figure 3.2.37 Hallside Field Trial –Year 3 Average Yields Against Treatments for all Clones

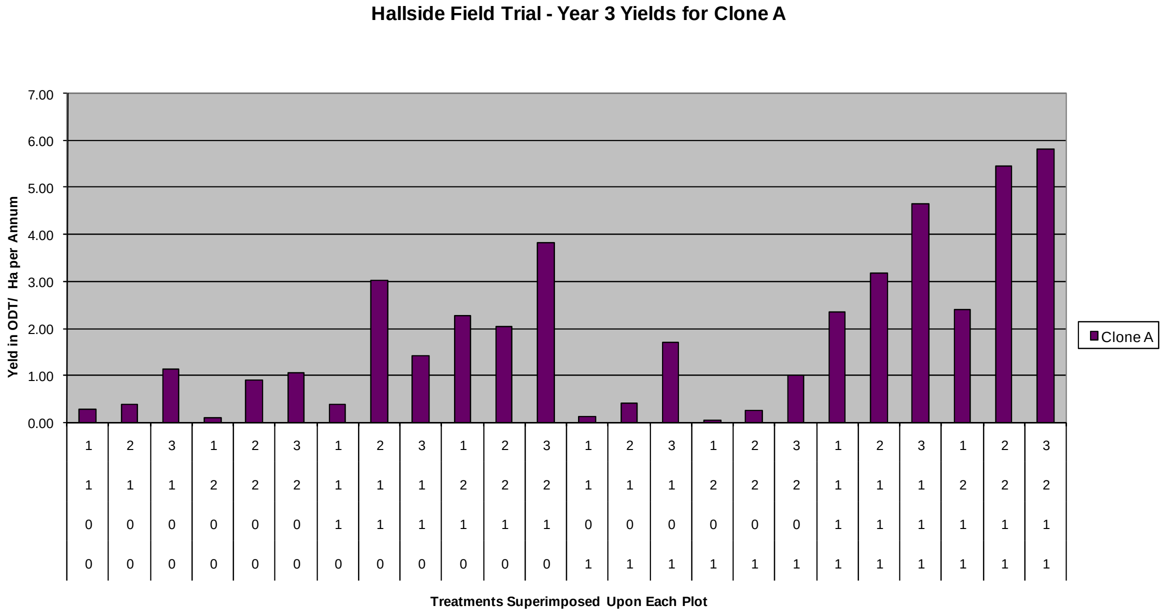


Figure 3.2.38 Hallside Field Trial –Year 3 Average Yields Against Treatments For Clone A

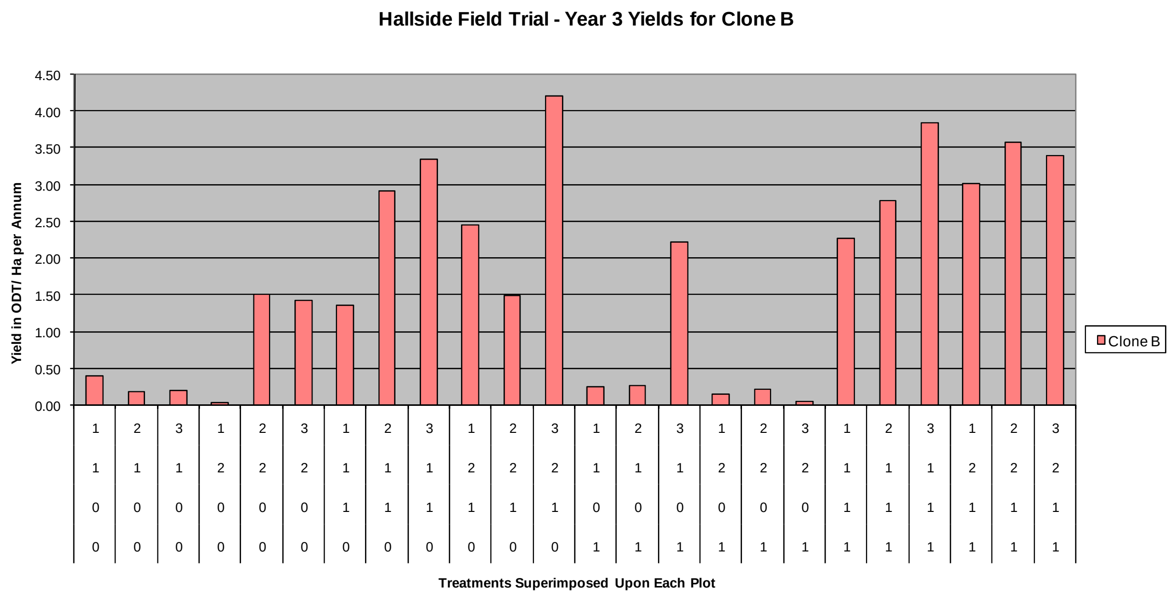


Figure 3.2.39 Hallside Field Trial –Year 3 Average Yields Against Treatments For Clone B

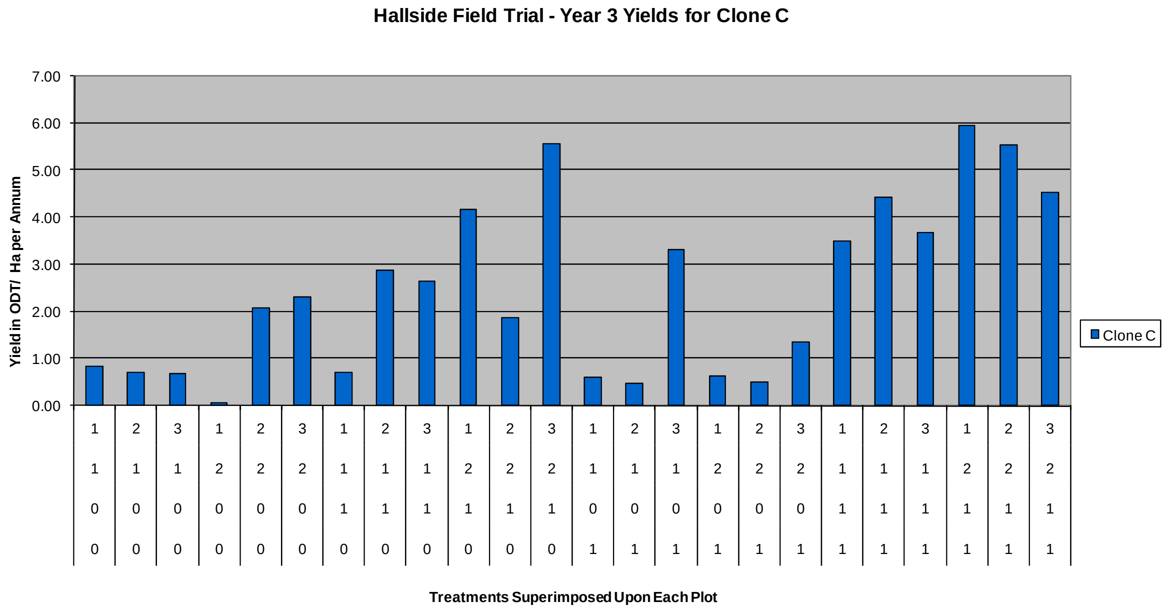


Figure 3.2.40 Hallside Field Trial –Year 3 Average Yields Against Treatments For Clone C

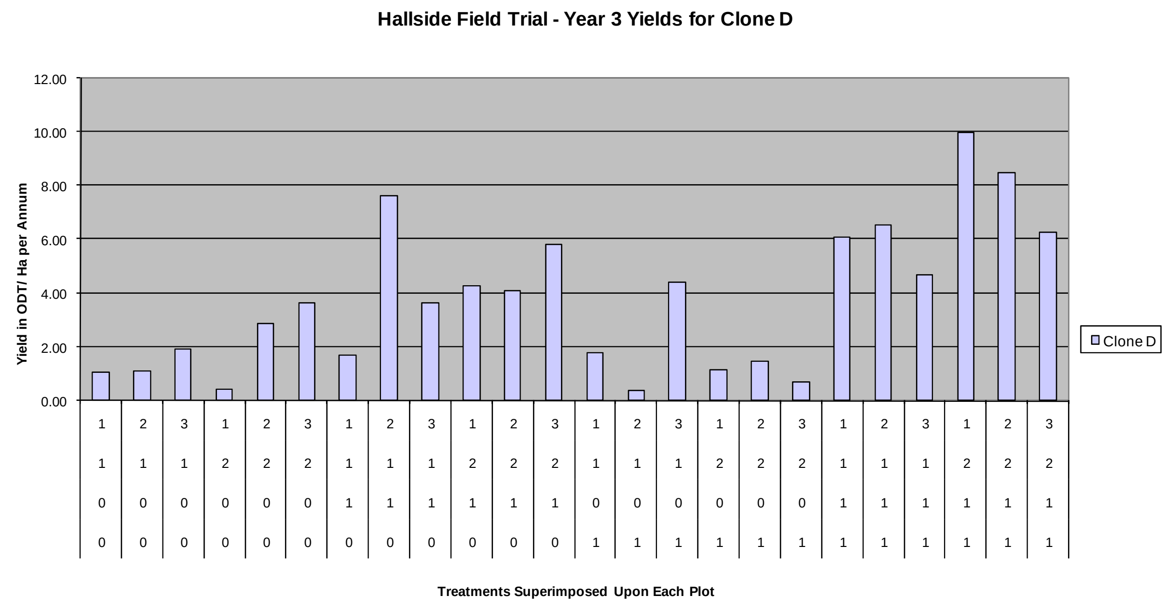


Figure 3.2.41 Hallside Field Trial –Year 3 Average Yields Against Treatments For Clone D

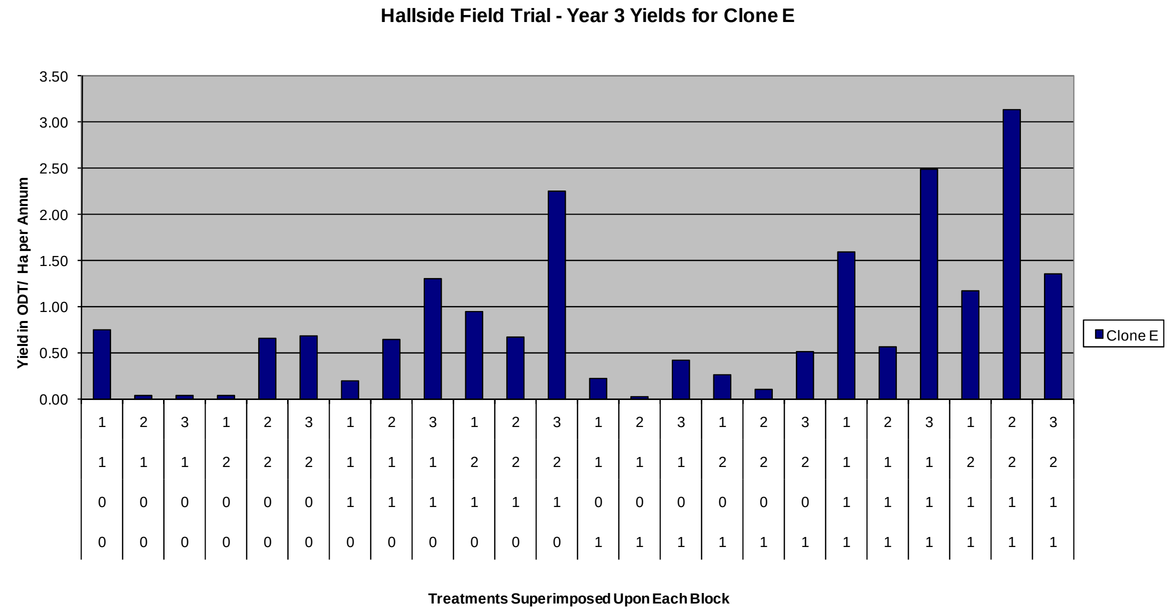


Figure 3.2.42 Hallside Field Trial –Year 3 Average Yields Against Treatments For Clone E

D. Hallside Field Trial – Cumulative Yields over 3 Years for all Clones

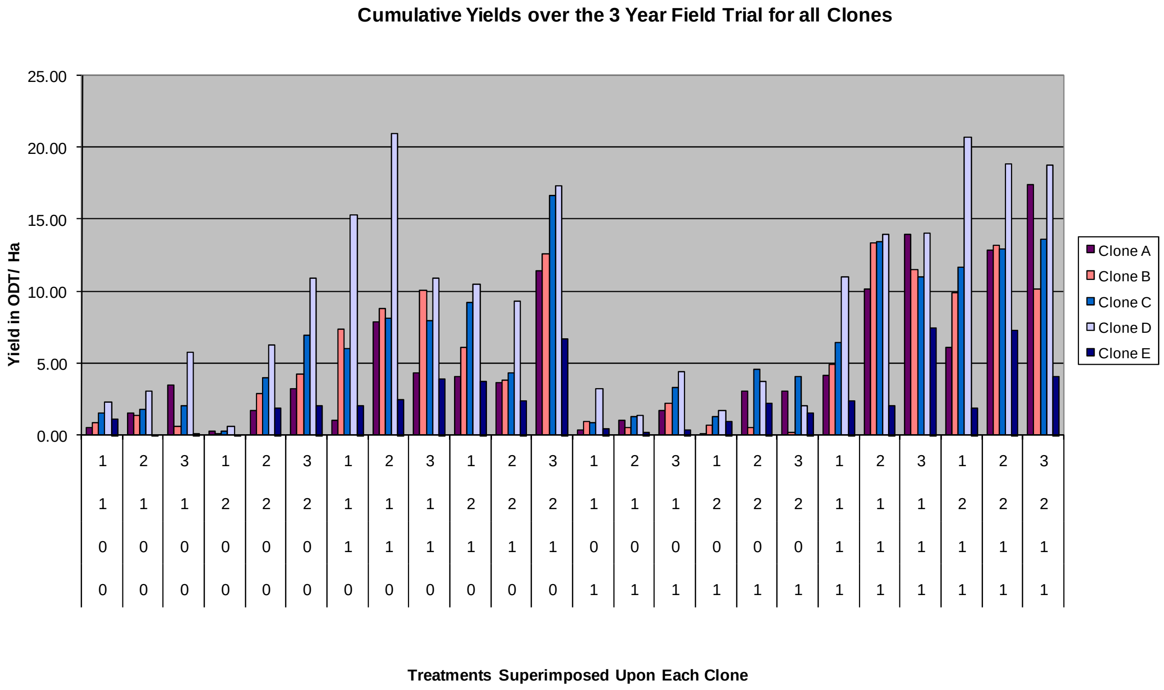


Figure 3.2.43 Hallside Field Trial –Cumulative Yield Totals for the 3 Year Field Trial

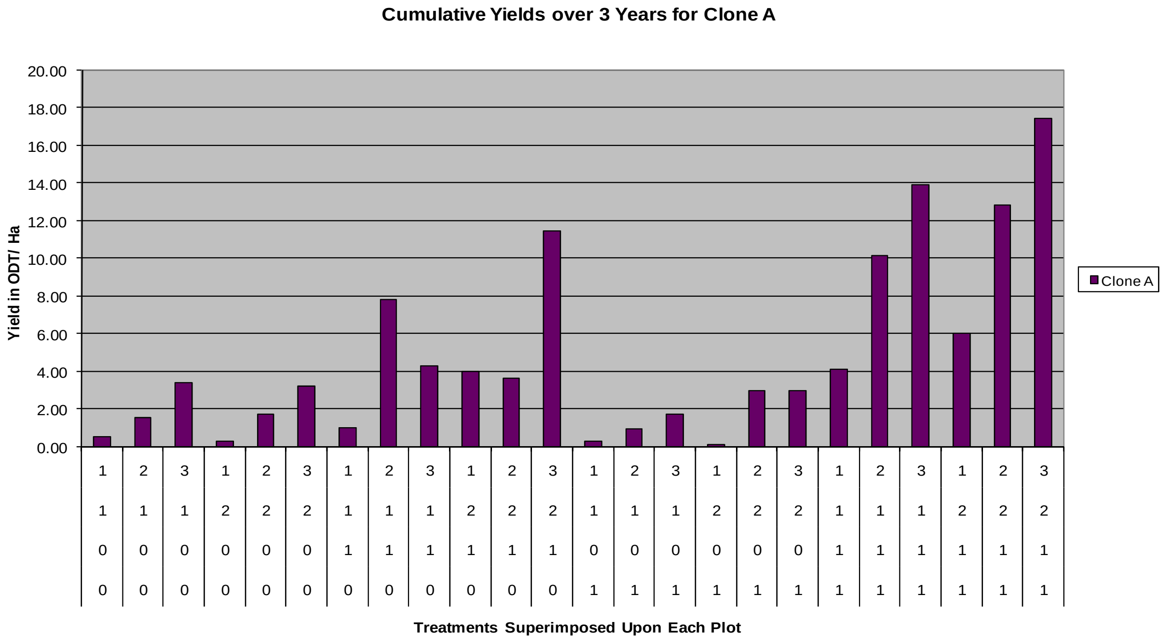


Figure 3.2.44 Hallside Field Trial –Cumulative Yield Totals for the 3 Year Field Trial for Clone A

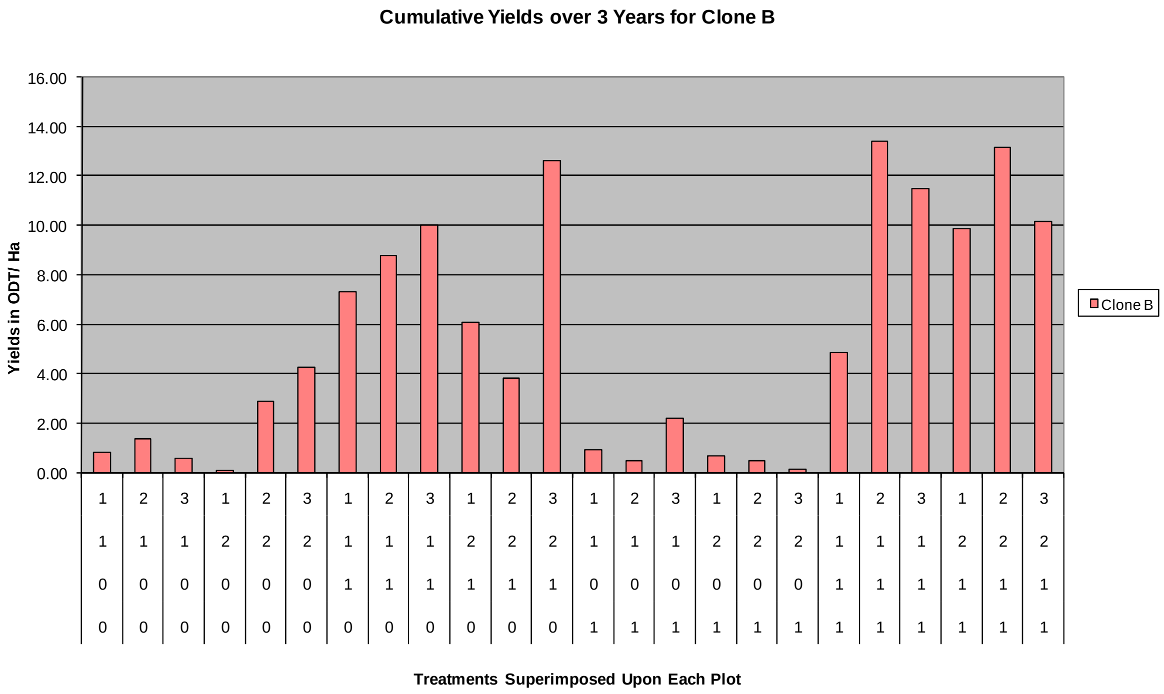


Figure 3.2.45 Hallside Field Trial –Cumulative Yield Totals for the 3 Year Field Trial for Clone B

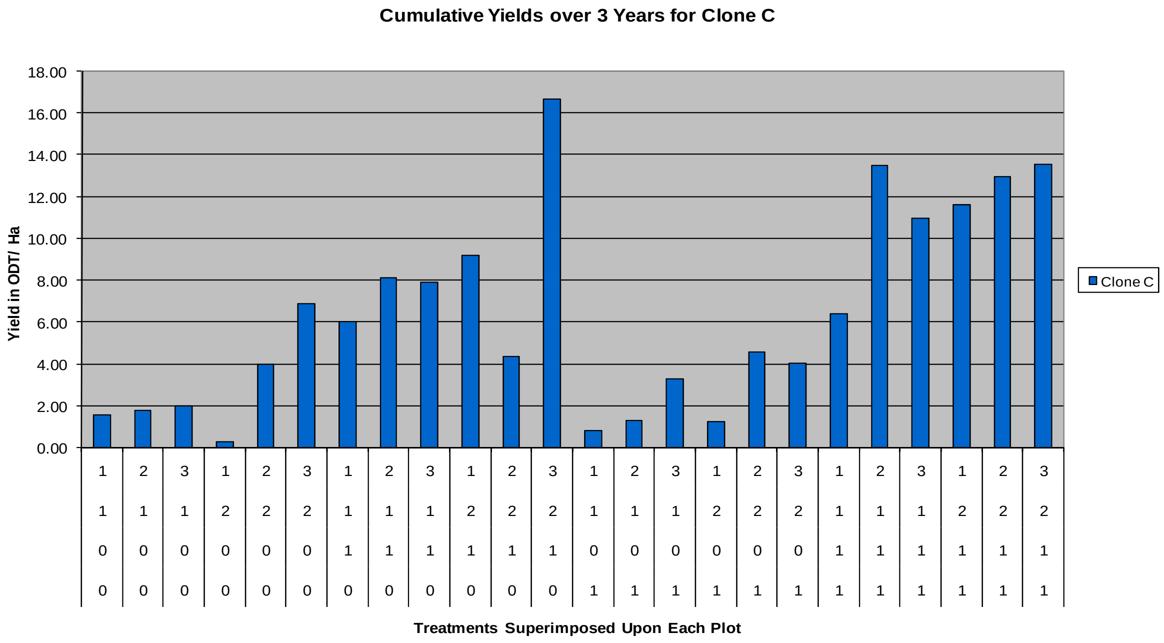


Figure 3.2.46 Hallside Field Trial –Cumulative Yield Totals for the 3 Year Field Trial for Clone C

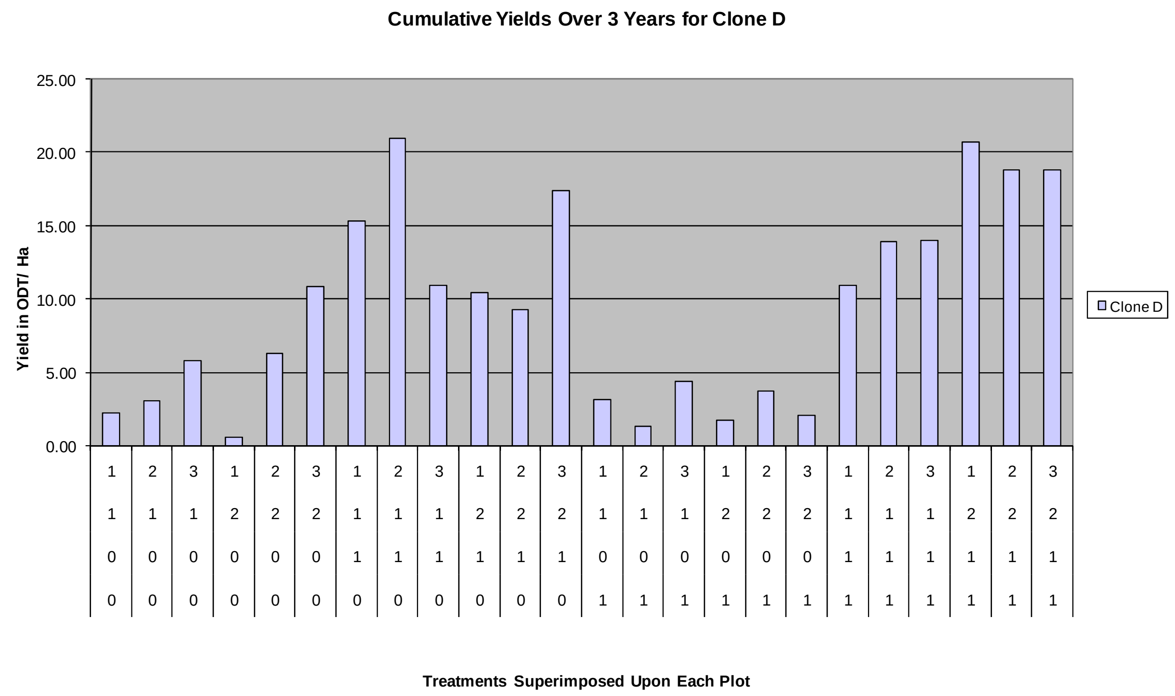


Figure 3.2.47 Hallside Field Trial –Cumulative Yield Totals for the 3 Year Field Trial for Clone D

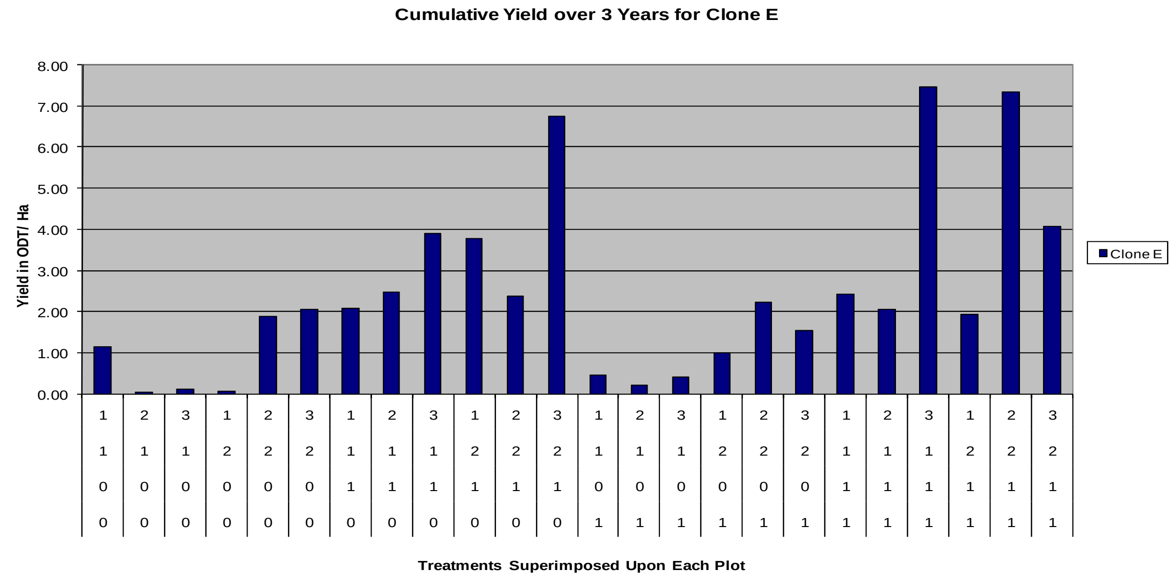


Figure 3.2.48 Hallside Field Trial –Cumulative Yield Totals for the 3 Year Field Trial for Clone E

3.3 Statistical Analysis of the Survival and Yields Obtained from the Field Trial

Interpreting the results of the field trial on the basis of the histograms reproduced above is insufficient to determine the complexities and interactions that are occurring between all the variables of the experiment.

The site on which the study was undertaken was divided into 72 plots arranged into 3 blocks (for practical reasons only) of 24 plots. Each plot was planted with 5 clones of willow labelled A – E and subjected to the following treatment variables -

Variable	No. of Levels			
Herbicide	2	Present	Absent	
Fertiliser	2	Present	Absent	
Spacing	2	1.0 m	0.5 m	
Coppicing	3	None	Once	Twice

Figure 3.3.1 Treatment Variables at the Hallside Field Trial

In the statistical analysis tables clones A-E are occasionally represented by the numbers 1-5, where A = 1, B=2 etc.

3.3.1 Subjective Analysis of the Survival in the First Year (1997)

Table 3.6 provides the overall percentage survival rates for each clone by treatment combination by block in year 1 of the field trial.

Table 3.6 Overall Mean Survivals for Treatment Combinations per Block for Year 1

[redacted]

* Highest Survival rates among the 5 clones are highlighted for each treatment combination in each block. All results are expressed as percentages.

A plot of the proportion of trees surviving at the end of the first year of the trial (Figure 3.3.2) shows a large spread in the results presenting difficulty in gaining a clear impression of any differences between clones. Each dot represents the proportion of trees surviving in each of the experimental plots. Values range from zero indicating that no stools survived under a particular treatment through to 1 where all stools had survived.

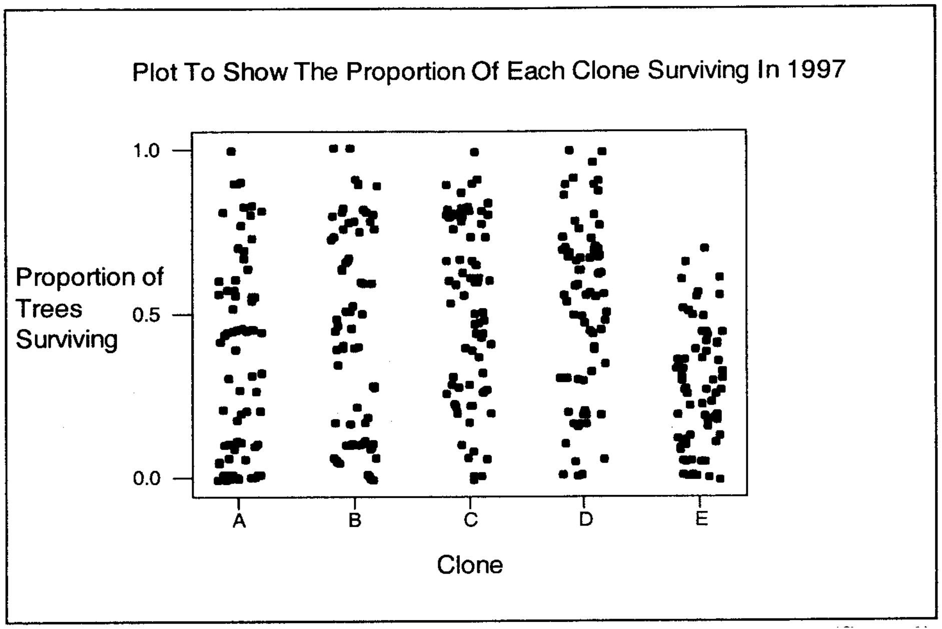


Figure 3.3.2 Plot to Show the Proportion of Each Clone Surviving in 1997

The use of 3 blocks in the experimental layout was adopted for practical reasons. When the frequency of the survival of the trees was plotted for each treatment combination by block (Figure 3.3.3), it was noted that the results were not consistent across the blocks, with what appeared to be a block effect, with plots in block 3 showing higher values than for those for blocks 1 and 2. This blocking effect was particularly evident when herbicide was not used. Whilst results for block 3 gave higher survival frequency, results for blocks 1 and 2 were similar.

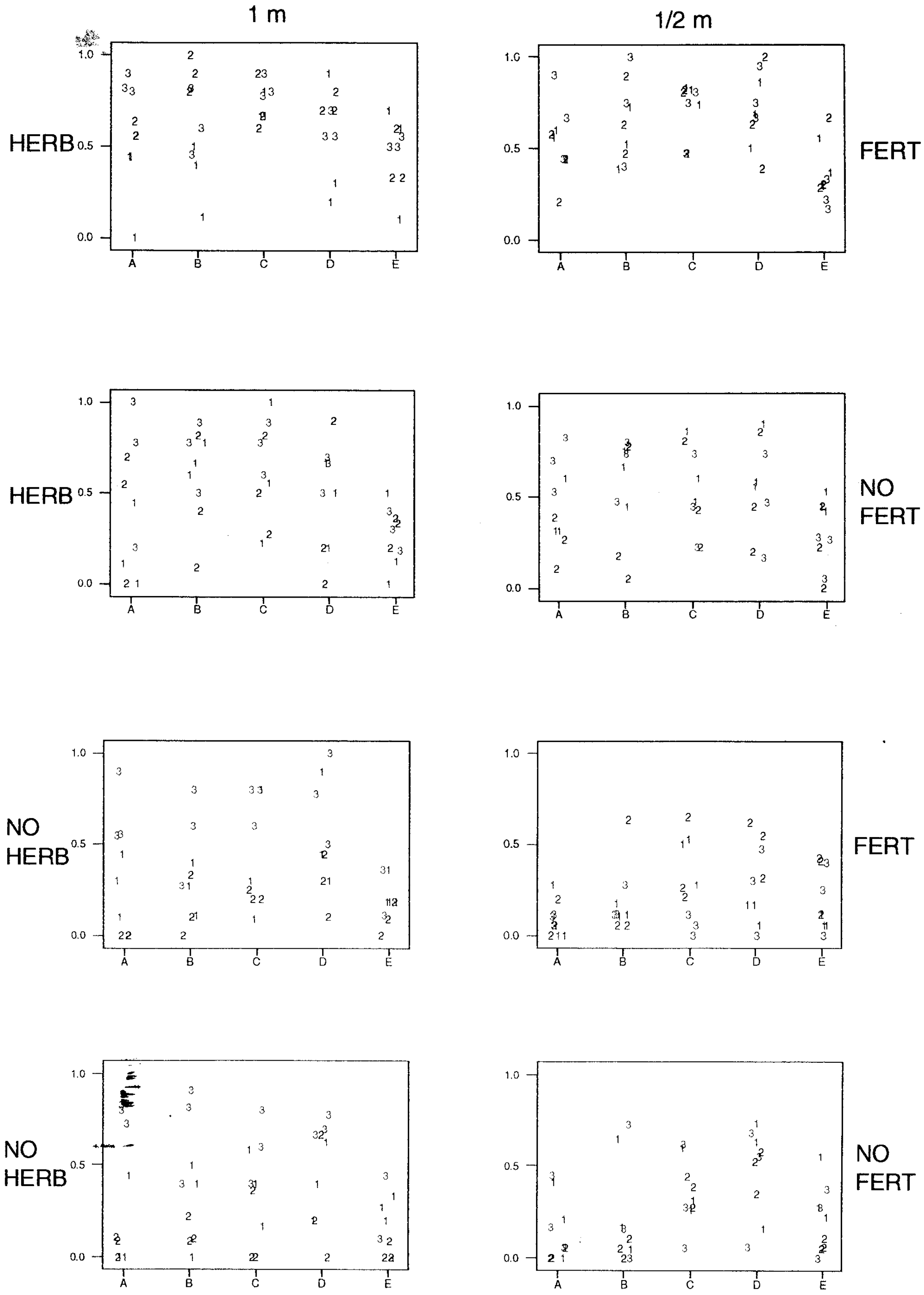


Figure 3.3.3 Plots to Show the Proportion of Trees Surviving For Each Clone For Each Treatment Combination by Block

3.3.2 Formal Analysis of the Survival in the First Year

To understand the complexity of the interactions between all the variables in the field trial, formal statistical analysis was undertaken of survival and yield data only as these were deemed to be the main outcomes of the study. Statistical analysis of the data was undertaken using Minitab Version 13 software with additional support being provided by Dilworth (2000).

For survival data, the proportions surviving was modelled using a binary logistic regression to examine the effect of the experimental variables (Grafen & Hails, 2002) and to fit a model that would identify which variables were having a significant effect on survival for the first year of growth. The results from the binary logistic regression from all 3 blocks combined are reproduced in Table 3.7. Significant results, those where p-values <0.05 indicating statistically significant effects are highlighted in bold numbering. Some but not all of the significant effects are highlighted on the effects of blocks 2 and 3 on increased survival and also the effect of block 3 in increasing the survival rates of Clones.

Due to the significant clone and block effect each individual block was modelled separately. Results for the binary logistic regression undertaken on individual blocks are reproduced in Tables 3.8. Significant values for survival are recorded for the effect of fertililiser, herbicide, and spacing interactions with the clones. These will be discussed further in Chapter 4.

Table 3.7 Results from the Binary Logistic Regression for Survival from all Three Blocks

```
Binary Logistic Regression

Link Function:  Logit
Response  Information

Variable  Value          Count
Survive   Success         2152
          Failure         3068
Plant     Total           5220

Logistic Regression Table
                                                         Odds       95% CI
Predictor               Coef      StDev        Z      P  Ratio    Lower    Upper
Constant             -1.0022     0.2060    -4.87  0.000
Clone
 2                    0.3556     0.2740     1.30  0.194   1.43     0.83     2.44
 3                    0.9273     0.2661     3.48  0.000   2.53     1.50     4.26
 4                    0.9800     0.2686     3.65  0.000   2.66     1.57     4.51
 5                   -0.2351     0.2946    -0.80  0.425   0.79     0.44     1.41
Fert
 1                  -0.21586    0.09068    -2.38  0.017   0.81     0.67     0.96
Herb
 1                    0.4252     0.2409     1.77  0.078   1.53     0.95     2.45
Space
 2                   -1.4092     0.2427    -5.81  0.000   0.24     0.15     0.39
Clone*Herb
 2*1                  0.2919     0.3230     0.90  0.366   1.34     0.71     2.52
 3*1                  0.4000     0.3234     1.24  0.216   1.49     0.79     2.81
 4*1                 -0.6092     0.3185    -1.91  0.056   0.54     0.29     1.02
 5*1                  0.2496     0.3413     0.73  0.465   1.28     0.66     2.51
Clone*Space
 2*2                  0.6557     0.3192     2.05  0.040   1.93     1.03     3.60
 3*2                  1.0731     0.3079     3.48  0.000   2.92     1.60     5.35
 4*2                  0.9933     0.3072     3.23  0.001   2.70     1.48     4.93
 5*2                  1.6594     0.3395     4.89  0.000   5.26     2.70    10.22
Fert*Herb
 1*1                  0.7602     0.1229     6.18  0.000   2.14     1.68     2.72
Herb*Space
 1*2                  1.4022     0.3135     4.47  0.000   4.06     2.20     7.51
Clone*Herb*Space
 2*1*2               -0.7299     0.4229    -1.73  0.084   0.48     0.21     1.10
 3*1*2               -1.2952     0.4174    -3.10  0.002   0.27     0.12     0.62
 4*1*2               -0.5549     0.4126    -1.35  0.179   0.57     0.26     1.29
 5*1*2               -1.8489     0.4384    -4.22  0.000   0.16     0.07     0.37
Block
 2                   -0.3938     0.1896    -2.08  0.038   0.67     0.47     0.98
 3                    1.2934     0.1801     7.18  0.000   3.65     2.56     5.19
Clone*Block
 2*2                  0.1736     0.2541     0.68  0.495   1.19     0.72     1.96
 2*3                 -0.6638     0.2455    -2.70  0.007   0.51     0.32     0.83
 3*2                 -0.0263     0.2479    -0.11  0.915   0.97     0.60     1.58
 3*3                 -1.5107     0.2413    -6.26  0.000   0.22     0.14     0.35
 4*2                  0.4259     0.2454     1.74  0.083   1.53     0.95     2.48
 4*3                 -1.0355     0.2393    -4.33  0.000   0.36     0.22     0.57
 5*2                  0.0127     0.2566     0.05  0.961   1.01     0.61     1.67
 5*3                 -1.6661     0.2512    -6.63  0.000   0.19     0.12     0.31

Log-Likelihood = -3110.635
```

Table 3.8 Results from the Binary Logistic Regression for Survival from the Individual Blocks

Block 1

Binary Logistic Regression

```
Link Function:  Logit
Response  Information
Variable  Value         Count
Survive   Success         702
Plant     Failure        1716
          Total          2418
Logistic Regression Table
                                                                     Odds        95% CI
Predictor               Coef        StDev          Z      P     Ratio     Lower     Upper
Constant             -1.6157       0.2037      -7.93 0.000
Clone
 2                    0.3694       0.1561       2.37 0.018      1.45      1.07      1.96
 3                    0.7076       0.1492       4.74 0.000      2.03      1.51      2.72
 4                    0.5822       0.1516       3.84 0.000      1.79      1.33      2.41
 5                    0.1413       0.1629       0.87 0.386      1.15      0.84      1.59
Fert
 1                    0.1513       0.2353       0.64 0.520      1.16      0.73      1.84
Herb
 1                    0.3506       0.2334       1.50 0.133      1.42      0.90      2.24
Space
 2                    0.1683       0.2074       0.81 0.417      1.18      0.79      1.78
Fert*Herb
 1*1                 -0.0664       0.3209      -0.21 0.836      0.94      0.50      1.76
Fert*Space
 1*2                 -0.8937       0.3079      -2.90 0.004      0.41      0.22      0.75
Herb*Space
 1*2                  0.1441       0.2792       0.52 0.606      1.16      0.67      2.00
Fert*Herb*Space
 1*1*2                0.8583       0.4020       2.14 0.033      2.36      1.07      5.19

Log-Likelihood = -1404.026
```

Block 2

Binary Logistic Regression

```
Link Function:  Logit
Response  Information
Variable  Value         Count
Survive   Success         629
Plant     Failure        1772
          Total          2401

Logistic Regression Table
                                                          Odds        95% CI
Predictor          Coef       StDev         Z      P     Ratio     Lower     Upper
Constant        -3.8099      0.3976     -9.58 0.000
Clone
 2               1.2058      0.4179      2.89 0.004      3.34      1.47      7.58
 3               1.9106      0.3956      4.83 0.000      6.76      3.11     14.67
 4               2.2320      0.3887      5.74 0.000      9.32      4.35     19.96
 5               1.1955      0.4198      2.85 0.004      3.31      1.45      7.53
Fert
 1              0.45644     0.09759      4.68 0.000      1.58      1.30      1.91
Herb
 1               2.6902      0.4254      6.32 0.000     14.73      6.40     33.92
Space
 2               0.6359      0.1953      3.26 0.001      1.89      1.29      2.77
Clone*Herb
 2*1            -0.8483      0.4604     -1.84 0.065      0.43      0.17      1.06
 3*1            -1.4400      0.4382     -3.29 0.001      0.24      0.10      0.56
 4*1            -1.8154      0.4331     -4.19 0.000      0.16      0.07      0.38
 5*1            -1.3396      0.4675     -2.87 0.004      0.26      0.10      0.65
Herb*Space
 1*2            -0.7713      0.2305     -3.35 0.001      0.46      0.29      0.73

Log-Likelihood = -1286.633
```

Block 3

Binary Logistic Regression

```
Link Function:  Logit
Response  Information
Variable  Value           Count
Survive   Success           821
Plant     Failure          1732
          Total            2553

Logistic Regression Table
                                                             Odds       95% CI
Predictor                  Coef       StDev        Z     P   Ratio    Lower    Upper
Constant                -0.1611      0.2040    -0.79 0.430
Clone
 2                      -0.1382      0.2811    -0.49 0.623    0.87     0.50     1.51
 3                      -0.0707      0.2827    -0.25 0.802    0.93     0.54     1.62
 4                       0.0284      0.2821     0.10 0.920    1.03     0.59     1.79
 5                      -1.2978      0.3715    -3.49 0.000    0.27     0.13     0.57
Herb
 1                      -0.2299      0.2907    -0.79 0.429    0.79     0.45     1.40
Fert
 1                      -0.3395      0.1378    -2.46 0.014    0.71     0.54     0.93
Herb*Fert
 1*1                     0.5285      0.1786     2.96 0.003    1.70     1.20     2.41
Space
 2                      -1.5181      0.3203    -4.74 0.000    0.22     0.12     0.41
Clone*Herb
 2*1                     0.0245      0.3997     0.06 0.951    1.02     0.47     2.24
 3*1                     0.1265      0.3984     0.32 0.751    1.13     0.52     2.48
 4*1                    -0.2187      0.4060    -0.54 0.590    0.80     0.36     1.78
 5*1                     0.6716      0.4852     1.38 0.166    1.96     0.76     5.07
Clone*Space
 2*2                     0.5830      0.4343     1.34 0.180    1.79     0.76     4.20
 3*2                     0.2449      0.4462     0.55 0.583    1.28     0.53     3.06
 4*2                     0.7639      0.4212     1.81 0.070    2.15     0.94     4.90
 5*2                     1.5891      0.5034     3.16 0.002    4.90     1.83    13.14
Herb*Space
 1*2                     1.4230      0.4039     3.52 0.000    4.15     1.88     9.16
Clone*Herb*Space
 2*1*2                  -0.4541      0.5589    -0.81 0.417    0.64     0.21     1.90
 3*1*2                  -0.4610      0.5685    -0.81 0.417    0.63     0.21     1.92
 4*1*2                  -0.6518      0.5544    -1.18 0.240    0.52     0.18     1.54
 5*1*2                  -2.0966      0.6505    -3.22 0.001    0.12     0.03     0.44

Log-Likelihood = -1528.842
```

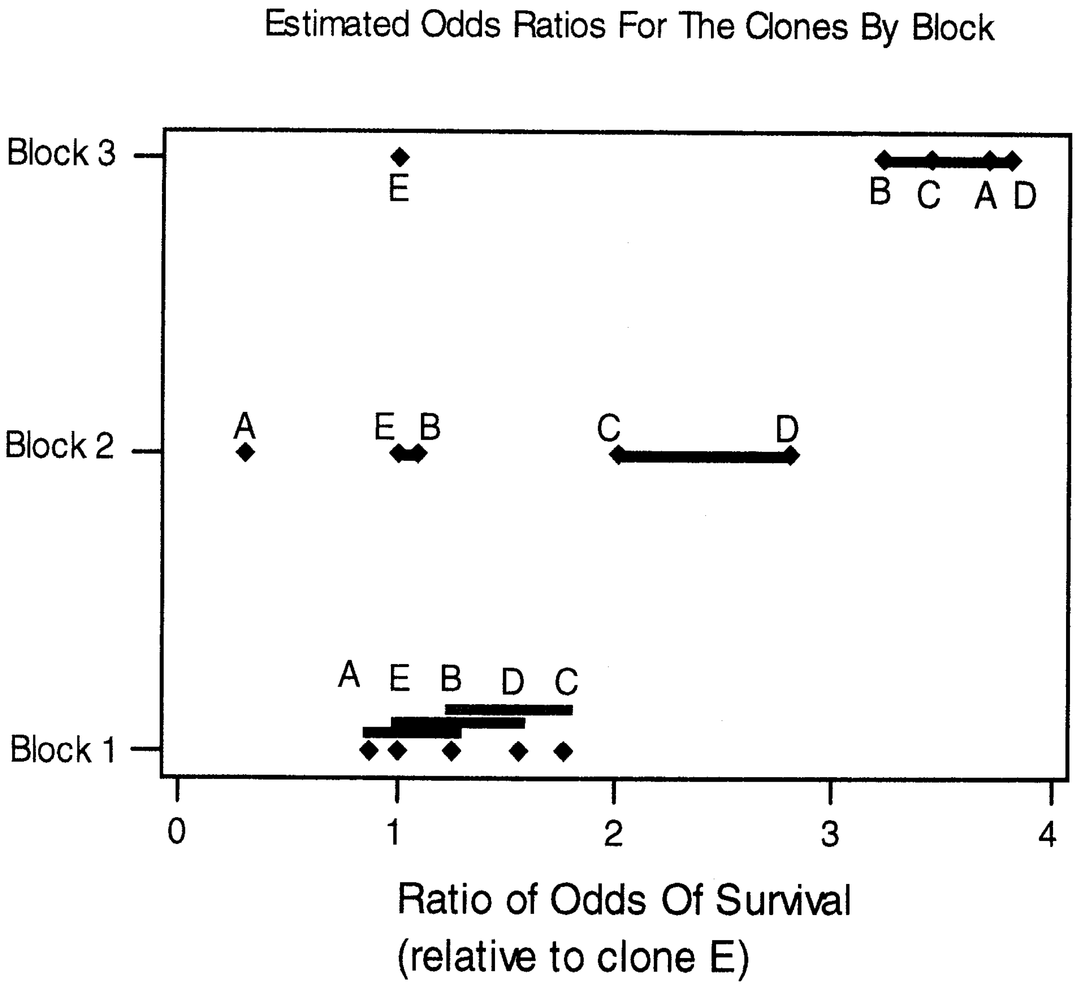


Figure 3.3.4 Estimated Odds Ratio by Block

The odds ratio for the 3 blocks of the effect of individual clones planted in the field trial relative to clone E, which is assumed to have an odds ratio of 1 were compared at the 95% significance level. These are plotted in Figure 3.3.4. Clones having an odds value > 1 suggest an increase in the chance of survival relative to clone E. Due to the variability of survival the odds ratios may also be expressed as a bar as opposed to a single point.

Significant results produced by the binary logistic regression fitted individually for each of the three blocks and their odds ratios and 95% confidence intervals are reproduced in Table 3.9.

Table 3.9 Odds Ratios and 95% confidence Intervals for significant Effects for Each Block Logistic Regression

Block 1

Variable	Odds Ratio	95% Confidence Interval
Fertiliser Present + 0.5m Spacing	**0.41**	**0.22 , 0.75**
Fertiliser + Herbicide Present + 0.5m Spacing	**2.36**	**1.07 , 5.19**

Block 2

	Odds Ratio	95% Confidence Interval
Fertiliser Present	**1.58**	**1.30 , 1.91**
Herbicide Present	**14.73**	**6.40 , 33.92**
0.5m Spacing	**1.89**	**1.29 , 2.77**
Clone C + Herbicide Present	**0.24**	**0.10 , 0.56**
Clone D + Herbicide Present	**0.16**	**0.07 , 0.38**
Clone E + Herbicide Present	**0.26**	**0.10 , 0.65**
Herbicide Present + 0.5m Spacing	**0.46**	**0.29 , 0.73**

Block 3

Variable	Odds Ratio	95% Confidence Interval
Fertiliser Present	**0.71**	**0.54 , 0.90**
0.5m Spacing	**0.22**	**0.12 , 0.40**
Clone E + 0.5m Spacing	**4.90**	**1.83 , 13.1**
Fertiliser + Herbicide Present	**1.70**	**1.20 , 2.40**
Herbicide present + 0.5m Spacing	**4.15**	**1.88 , 9.10**

3.3.3 Subjective Analysis of the Survival over the 3 Years of the Field Trial (1997-1999)

Survival over the 3 year period was included as an additional outcome; the effect of coppicing is additional to those results obtained in the first year. Overall percentage survivals for each block are shown in Tables 3.10 – 3.12.

Table 3.10 Mean Survivals for Treatment Combinations for Block 1 over 3 Years

[redacted]

* Highest Survival rates among the 5 clones are highlighted for each treatment combination in each block. All results are expressed as percentages.

Table 3.11 Mean Survivals for Treatment Combinations for Block 2 over 3 Years

[redacted]

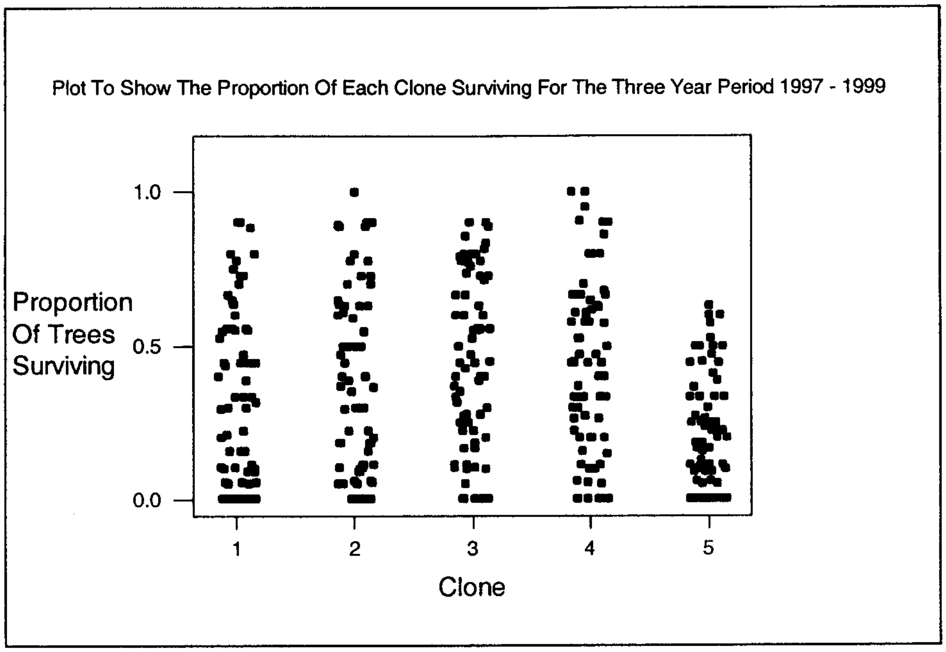
* Highest Survival rates among the 5 clones are highlighted for each treatment combination in each block. All results are expressed as percentages.

Table 3.12 Mean Survivals for Treatment Combinations for Block 3 over 3 Years

[redacted]

* Highest Survival rates among the 5 clones are highlighted for each treatment combination in each block. All results are expressed as percentages.

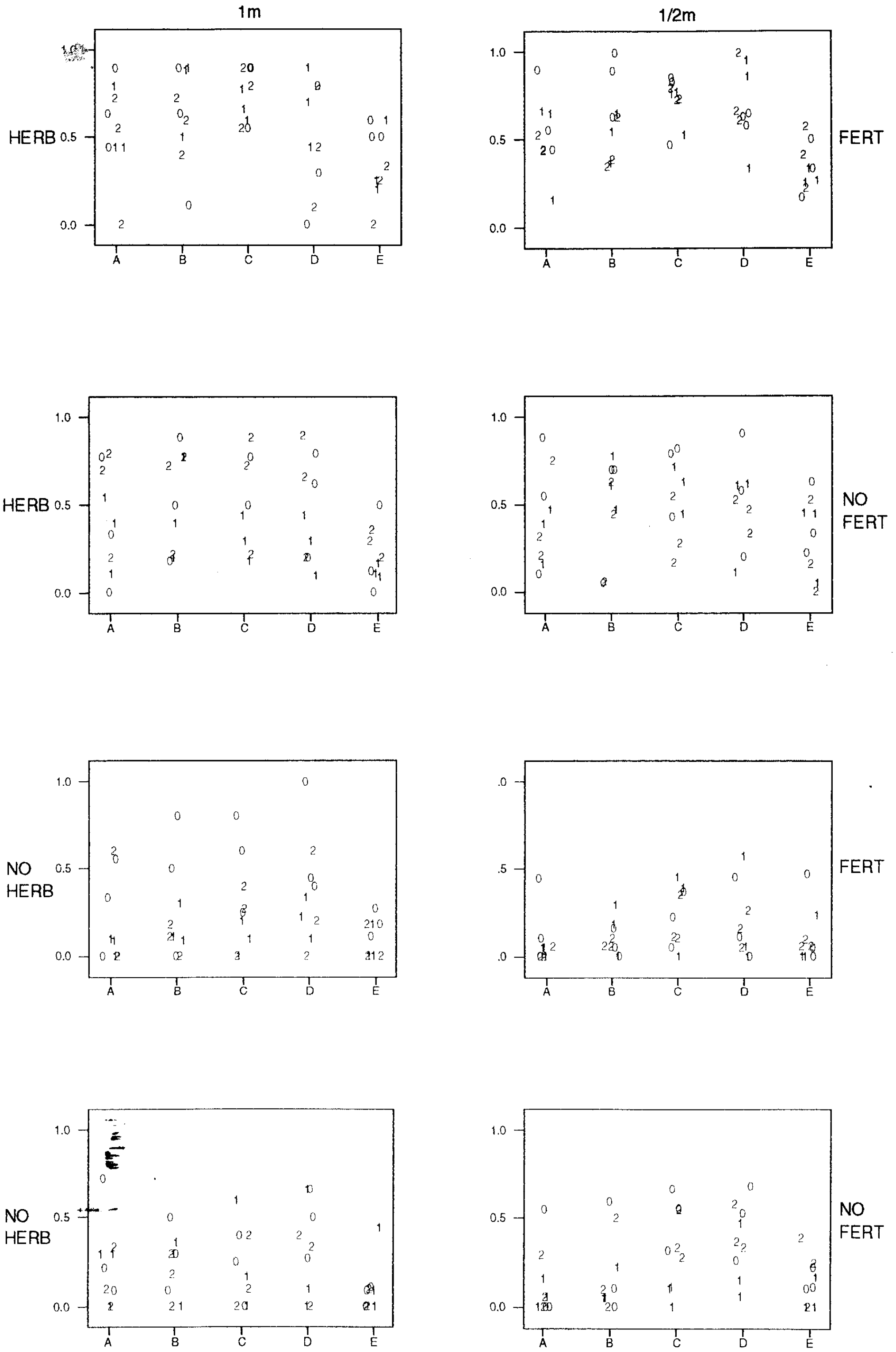
Figure 3.3.5 reproduced below shows the proportion of trees surviving for each clone over a 3 year time period. When compared to the proportions surviving after the first year there seems to be a slight decrease, however obtaining a clear picture of which clone survives best remains difficult.



* Clone 1, 2, 3, 4 & 5 refer to Clones A, B, C, D & E

Figure 3.3.5 Plot to Show the Proportion of Each Clone Surviving over the Three year period

Clone E is again viewed to be the poorest surviving of all clones, with clones B, C and D being viewed as having a higher proportion surviving. Clone A is viewed as having a higher proportion surviving than clone E, yet less than clones B, C and D.



* 0 – No Coppice, 1 – Coppiced Annually, 2 – Coppiced in Year 2

Figure 3.3.6 Plots to Show the Proportion of Trees Surviving For Each Clone For Each Treatment Combination by Coppice Effect

Comparison can be drawn between Figure 3.3.6 and Figure 3.3.3. Consideration of the additional variable, coppicing, would seem to indicate that survival rates are higher for those trees not coppiced compared with those that have been coppiced.

3.3.4 Formal Analysis of the Survival over Three Years

Binary logistic regression was again used to examine the relationship between the variables and the survival results to fit a model that would identify which variables were having a significant effect over the three year study. The results from the binary logistic regression from all 3 blocks combined are reproduced in Table 3.13.

Significant results, those where p-values <0.05 indicating statistically significant effects are again highlighted in bold numbering. Some but not all significant effects are highlighted on the effects of block 3 on increased survival of individual clones.

Again due to the significant clone and block effect each individual block was modelled separately. Results for the binary logistic regression undertaken on individual blocks are reproduced in Tables 3.14 - 16. Significant p-values for the interactions between treatments and clones are noted and will be discussed further in Chapter 4.

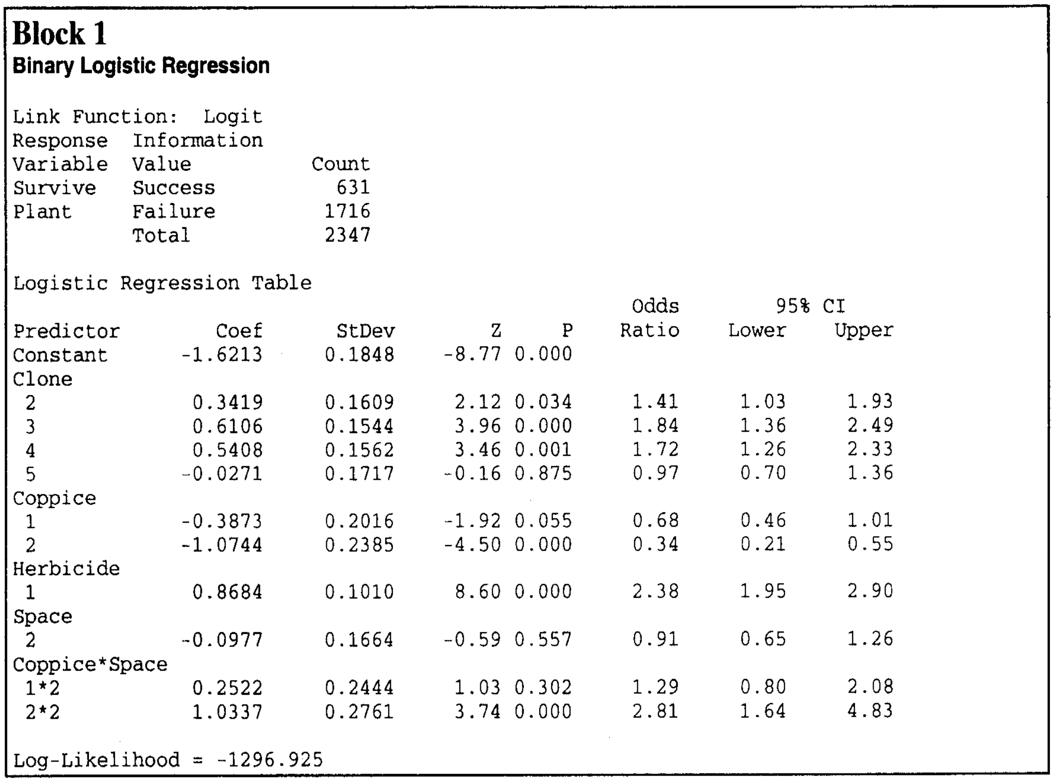
Table 3.13 Results from the Binary Logistic Regression for the Survival Data from all Three Blocks

```
Binary Logistic Regression

Link Function:  Logit
Response  Information
Variable  Value          Count
Survive   Success         1856
Plant     Failure         5220
          Total           7076
Logistic Regression Table
                                                           Odds       95% CI
Predictor              Coef       StDev         Z      P  Ratio    Lower    Upper
Constant            -1.8188      0.2044     -8.90  0.000
Clone
 2                   0.4456      0.2186      2.04  0.042   1.56     1.02     2.40
 3                   0.9234      0.2059      4.48  0.000   2.52     1.68     3.77
 4                   1.0263      0.2056      4.99  0.000   2.79     1.86     4.18
 5                   0.2003      0.2357      0.85  0.396   1.22     0.77     1.94
Fert
 1                  -0.4152      0.1262     -3.29  0.001   0.66     0.52     0.85
Herb
 1                   0.8209      0.1760      4.66  0.000   2.27     1.61     3.21
Space
 2                   0.2586      0.1057      2.45  0.014   1.30     1.05     1.59
Coppice
 1                  -0.5906      0.1534     -3.85  0.000   0.55     0.41     0.75
 2                  -0.5295      0.1505     -3.52  0.000   0.59     0.44     0.79
Block
 2                  -0.7244      0.2444     -2.96  0.003   0.48     0.30     0.78
 3                   1.1182      0.2124      5.26  0.000   3.06     2.02     4.64
Clone*Herb
 2*1                -0.1411      0.2037     -0.69  0.489   0.87     0.58     1.29
 3*1                -0.4413      0.1924     -2.29  0.022   0.64     0.44     0.94
 4*1                -0.7178      0.1917     -3.74  0.000   0.49     0.34     0.71
 5*1                -0.3169      0.2249     -1.41  0.159   0.73     0.47     1.13
Clone*Block
 2*2                 0.1117      0.2436      0.46  0.647   1.12     0.69     1.80
 2*3                -0.4382      0.2158     -2.03  0.042   0.65     0.42     0.98
 3*2                 0.2173      0.2313      0.94  0.347   1.24     0.79     1.96
 3*3                -0.6314      0.2091     -3.02  0.003   0.53     0.35     0.80
 4*2                 0.2746      0.2328      1.18  0.238   1.32     0.83     2.08
 4*3                -0.5755      0.2104     -2.73  0.006   0.56     0.37     0.85
 5*2                 0.1097      0.2579      0.43  0.670   1.12     0.67     1.85
 5*3                -0.9659      0.2454     -3.94  0.000   0.38     0.24     0.62
Fert*Herb
 1*1                 0.5216      0.1206      4.32  0.000   1.68     1.33     2.13
Fert*Block
 1*2                 0.5102      0.1419      3.60  0.000   1.67     1.26     2.20
 1*3                 0.0143      0.1347      0.11  0.915   1.01     0.78     1.32
Herb*Coppice
 1*1                 0.5331      0.1476      3.61  0.000   1.70     1.28     2.28
 1*2                 0.3055      0.1434      2.13  0.033   1.36     1.02     1.80
Space*Block
 2*2                -0.1137      0.1521     -0.75  0.455   0.89     0.66     1.20
 2*3                -0.7009      0.1428     -4.91  0.000   0.50     0.38     0.66
Coppice*Block
 1*2                 0.1960      0.1702      1.15  0.249   1.22     0.87     1.70
 1*3                -0.3444      0.1635     -2.11  0.035   0.71     0.51     0.98
 2*2                 0.2603      0.1719      1.51  0.130   1.30     0.93     1.82
 2*3                -0.0035      0.1623     -0.02  0.983   1.00     0.73     1.37

Log-Likelihood = -3796.880
```

Table 3.14 Results from the Binary Logistic Regression for the Survival Data from Block 1



Block 1

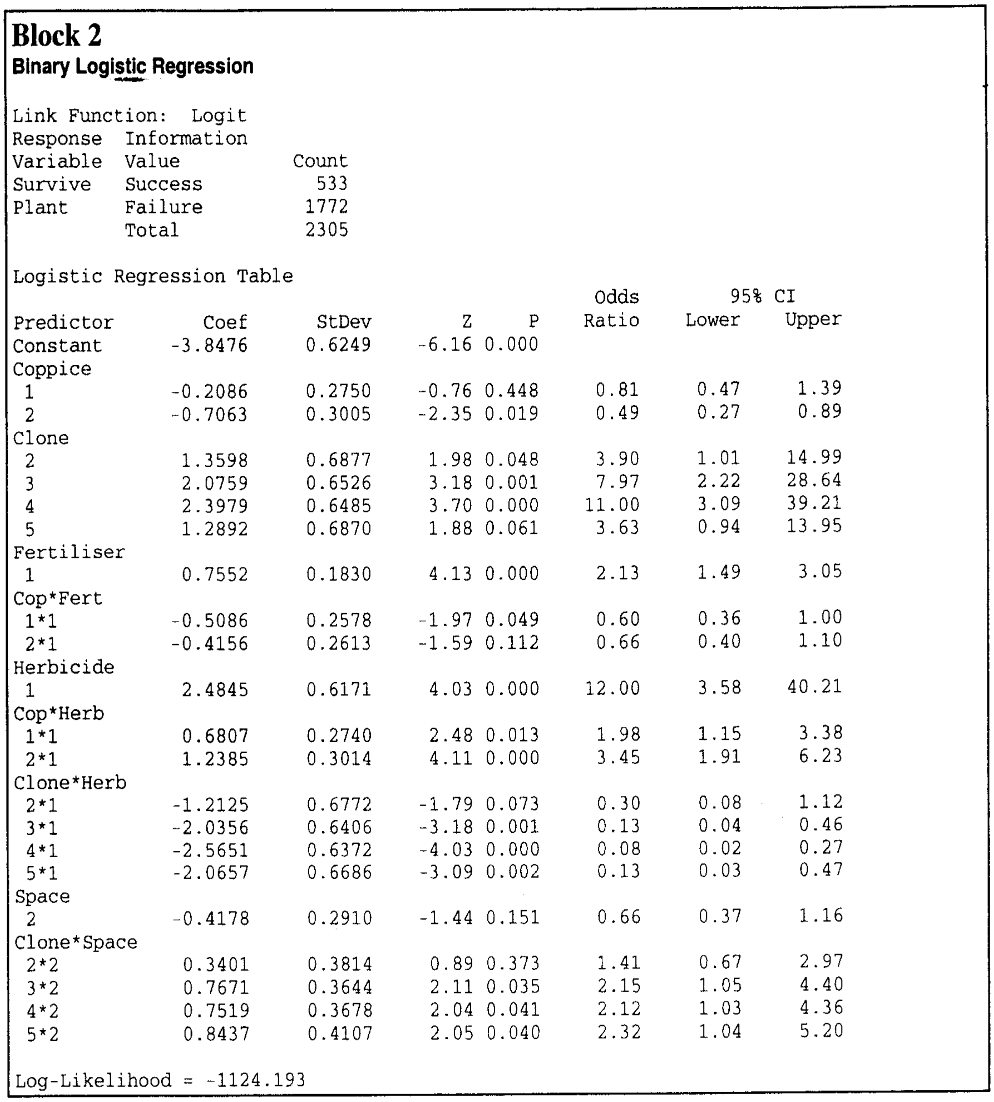
Binary Logistic Regression

```
Link Function:  Logit
Response  Information
Variable  Value          Count
Survive   Success          631
Plant     Failure         1716
          Total           2347

Logistic Regression Table
                                                    Odds        95% CI
Predictor        Coef       StDev         Z      P   Ratio     Lower     Upper
Constant      -1.6213      0.1848     -8.77  0.000
Clone
 2             0.3419      0.1609      2.12  0.034    1.41      1.03      1.93
 3             0.6106      0.1544      3.96  0.000    1.84      1.36      2.49
 4             0.5408      0.1562      3.46  0.001    1.72      1.26      2.33
 5            -0.0271      0.1717     -0.16  0.875    0.97      0.70      1.36
Coppice
 1            -0.3873      0.2016     -1.92  0.055    0.68      0.46      1.01
 2            -1.0744      0.2385     -4.50  0.000    0.34      0.21      0.55
Herbicide
 1             0.8684      0.1010      8.60  0.000    2.38      1.95      2.90
Space
 2            -0.0977      0.1664     -0.59  0.557    0.91      0.65      1.26
Coppice*Space
 1*2           0.2522      0.2444      1.03  0.302    1.29      0.80      2.08
 2*2           1.0337      0.2761      3.74  0.000    2.81      1.64      4.83

Log-Likelihood = -1296.925
```

Table 3.15 Results from the Binary Logistic Regression for the Survival Data from Block 2



Block 2

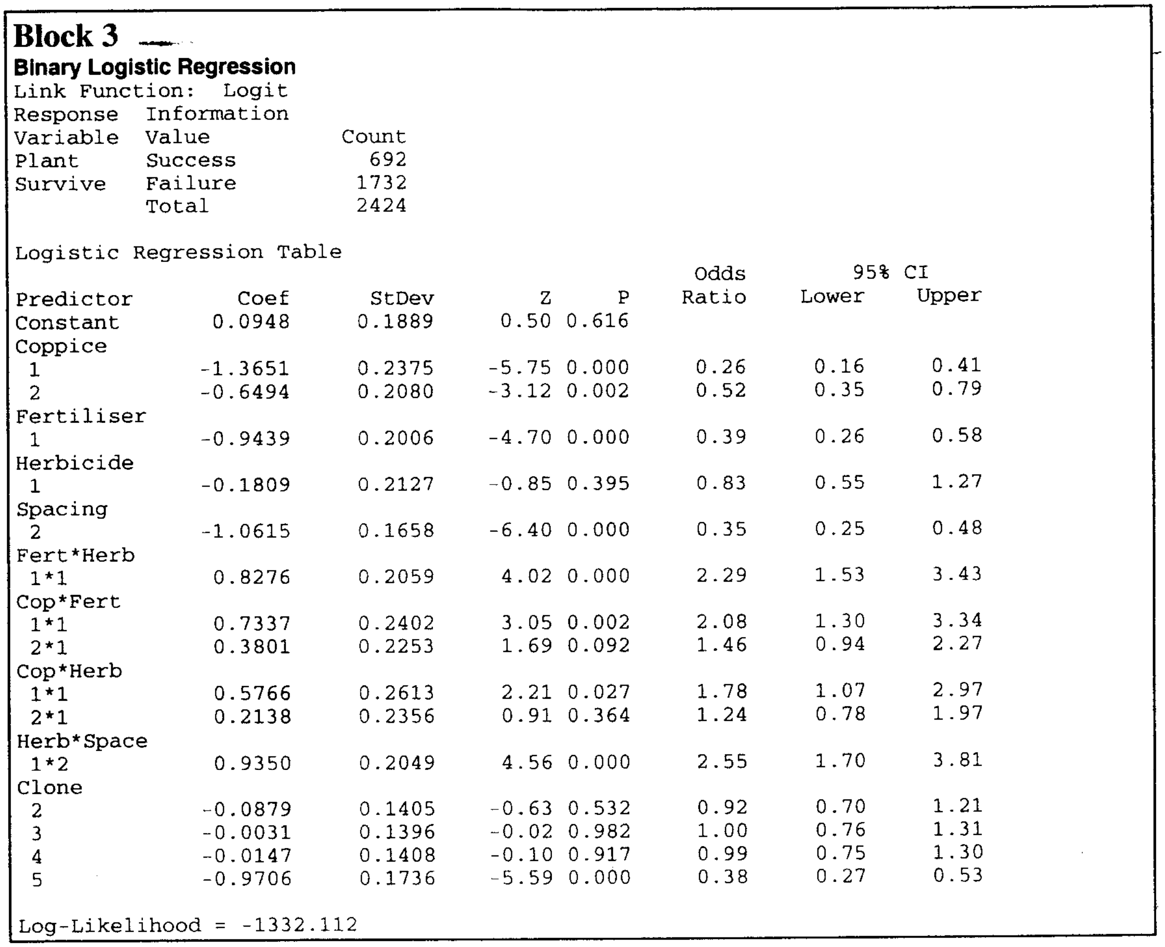
Binary Logistic Regression

```
Link Function:  Logit
Response  Information
Variable  Value         Count
Survive   Success         533
Plant     Failure        1772
          Total          2305

Logistic Regression Table
                                                       Odds       95% CI
Predictor         Coef      StDev       Z      P      Ratio    Lower    Upper
Constant       -3.8476     0.6249   -6.16  0.000
Coppice
 1             -0.2086     0.2750   -0.76  0.448       0.81     0.47     1.39
 2             -0.7063     0.3005   -2.35  0.019       0.49     0.27     0.89
Clone
 2              1.3598     0.6877    1.98  0.048       3.90     1.01    14.99
 3              2.0759     0.6526    3.18  0.001       7.97     2.22    28.64
 4              2.3979     0.6485    3.70  0.000      11.00     3.09    39.21
 5              1.2892     0.6870    1.88  0.061       3.63     0.94    13.95
Fertiliser
 1              0.7552     0.1830    4.13  0.000       2.13     1.49     3.05
Cop*Fert
 1*1           -0.5086     0.2578   -1.97  0.049       0.60     0.36     1.00
 2*1           -0.4156     0.2613   -1.59  0.112       0.66     0.40     1.10
Herbicide
 1              2.4845     0.6171    4.03  0.000      12.00     3.58    40.21
Cop*Herb
 1*1            0.6807     0.2740    2.48  0.013       1.98     1.15     3.38
 2*1            1.2385     0.3014    4.11  0.000       3.45     1.91     6.23
Clone*Herb
 2*1           -1.2125     0.6772   -1.79  0.073       0.30     0.08     1.12
 3*1           -2.0356     0.6406   -3.18  0.001       0.13     0.04     0.46
 4*1           -2.5651     0.6372   -4.03  0.000       0.08     0.02     0.27
 5*1           -2.0657     0.6686   -3.09  0.002       0.13     0.03     0.47
Space
 2             -0.4178     0.2910   -1.44  0.151       0.66     0.37     1.16
Clone*Space
 2*2            0.3401     0.3814    0.89  0.373       1.41     0.67     2.97
 3*2            0.7671     0.3644    2.11  0.035       2.15     1.05     4.40
 4*2            0.7519     0.3678    2.04  0.041       2.12     1.03     4.36
 5*2            0.8437     0.4107    2.05  0.040       2.32     1.04     5.20

Log-Likelihood = -1124.193
```

Table 3.16 Results from the Binary Logistic Regression for the Survival Data from Block 3



Block 3

Binary Logistic Regression

```
Link Function:  Logit
Response  Information
Variable  Value          Count
Plant     Success          692
Survive   Failure         1732
          Total           2424

Logistic Regression Table
                                                       Odds        95% CI
Predictor          Coef       StDev        Z      P   Ratio     Lower    Upper
Constant         0.0948      0.1889     0.50  0.616
Coppice
 1              -1.3651      0.2375    -5.75  0.000    0.26      0.16     0.41
 2              -0.6494      0.2080    -3.12  0.002    0.52      0.35     0.79
Fertiliser
 1              -0.9439      0.2006    -4.70  0.000    0.39      0.26     0.58
Herbicide
 1              -0.1809      0.2127    -0.85  0.395    0.83      0.55     1.27
Spacing
 2              -1.0615      0.1658    -6.40  0.000    0.35      0.25     0.48
Fert*Herb
 1*1             0.8276      0.2059     4.02  0.000    2.29      1.53     3.43
Cop*Fert
 1*1             0.7337      0.2402     3.05  0.002    2.08      1.30     3.34
 2*1             0.3801      0.2253     1.69  0.092    1.46      0.94     2.27
Cop*Herb
 1*1             0.5766      0.2613     2.21  0.027    1.78      1.07     2.97
 2*1             0.2138      0.2356     0.91  0.364    1.24      0.78     1.97
Herb*Space
 1*2             0.9350      0.2049     4.56  0.000    2.55      1.70     3.81
Clone
 2              -0.0879      0.1405    -0.63  0.532    0.92      0.70     1.21
 3              -0.0031      0.1396    -0.02  0.982    1.00      0.76     1.31
 4              -0.0147      0.1408    -0.10  0.917    0.99      0.75     1.30
 5              -0.9706      0.1736    -5.59  0.000    0.38      0.27     0.53

Log-Likelihood = -1332.112
```

The odds ratio for the 3 blocks over 3 years growth of the effect on individual clones planted in the field trial relative to clone E, which is assumed to have an odds ratio of 1, were compared at the 95% significance level. These are plotted in Figure 3.3.7. Clones having an odds value > 1 suggest an increase in the chance of survival relative to clone E.

Significant results produced by the binary logistic regression fitted individually for each of the three blocks and their odds ratios and 95% confidence intervals are reproduced in Table 3.17.

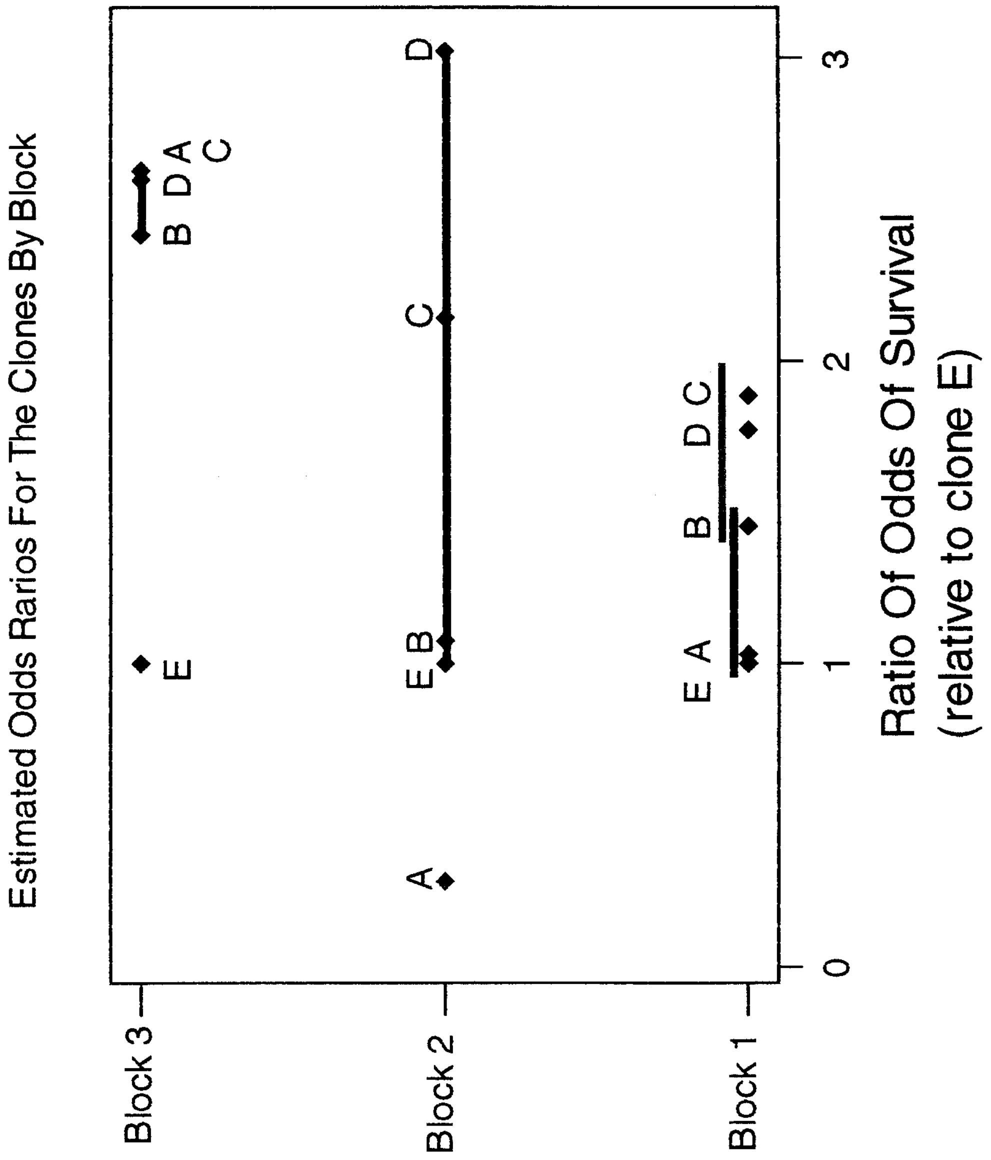


Figure 3.3.7 Estimated Odds Ratio for the Clones by Block

Table 3.17 Estimated Odds Ratios and 95 % Confidence Intervals for Significant Effects for Individual Block Logistic Regression

Block 1

Variable	Odds Ratio	95% Confidence Interval
Coppice Twice	**0.34**	**0.21 , 0.55**
Herbicide Present	**2.38**	**1.95 , 2.90**
Coppice Twice + 0.5m Spacing	**2.81**	**1.64 , 4.83**

Block 2

Variable	Odds Ratio	95% Confidence Interval
Fertiliser Present	**2.13**	**1.49 , 3.05**
Herbicide Present	**12.00**	**3.58 , 40.21**
Coppice Twice	**0.49**	**0.27 , 0.89**
Coppice Once + Herbicide Present	**1.98**	**1.15 , 3.38**
Coppice Twice + Herbicide Present	**3.45**	**1.91 , 6.23**
Clone C + Herbicide present	**0.13**	**0.04 , 0.46**
Clone D + Herbicide Present	**0.08**	**0.02 , 0.27**
Clone E + Herbicide Present	**0.13**	**0.03 , 0.47**
Clone C + 0.5m Spacing	**2.15**	**1.05 , 4.40**
Clone D + 0.5m Spacing	**2.12**	**1.03 , 4.36**
Clone E + 0.5m Spacing	**2.32**	**1.04 , 5.20**

Block 3

Variable	Odds Ratio	95% Confidence Interval
Coppice Once	**0.26**	**0.16 , 0.41**
Coppice Twice	**0.52**	**0.35 , 0.79**
Fertiliser Present	**0.39**	**0.26 , 0.58**
0.5m Spacing	**0.35**	**0.25 , 0.48**
Fertiliser + Herbicide Present	**2.29**	**1.53 , 3.43**
Coppice Once + Fertiliser Present	**2.08**	**1.30 , 3.34**
Coppice Once + Herbicide Present	**1.78**	**1.07 , 2.97**
0.5m Spacing + Herbicide Present	**2.55**	**1.70 , 3.81**

3.3.5 Subjective Analysis of the Total Yield over the 3 Years of the Field Trial

Analysing the yield against treatment and clone represents a useful tool in the assessment of clones both for financial gain through the sale of the raw material and when considering the total metal uptake by individual clones.

A plot to show the total yield produced per clone over a three year period (Figure 3.3.8) suggests that clone D performs well while clone E performs the worst. Evidence from the plot suggest that clone A produces high yield, however closer examination shows these results to have come from block 3.

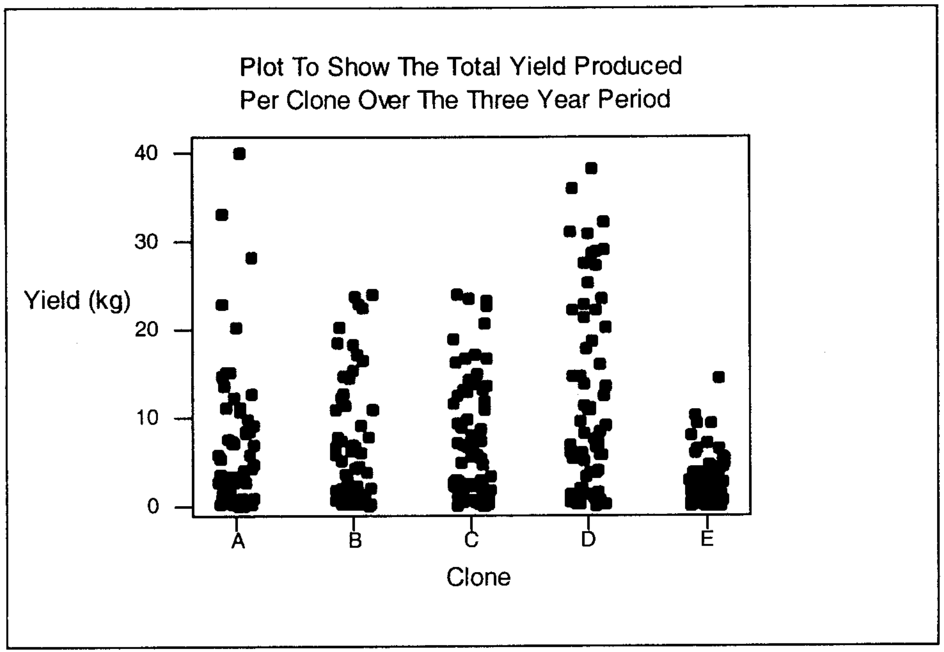


Figure 3.3.8 Plot to Show the Total Yield Produced per Clone over the Three Year Period

Further subjective analyse of the influence of the effect of the clones upon yield are reproduced in Figures 3.3.9 and 3.3.10

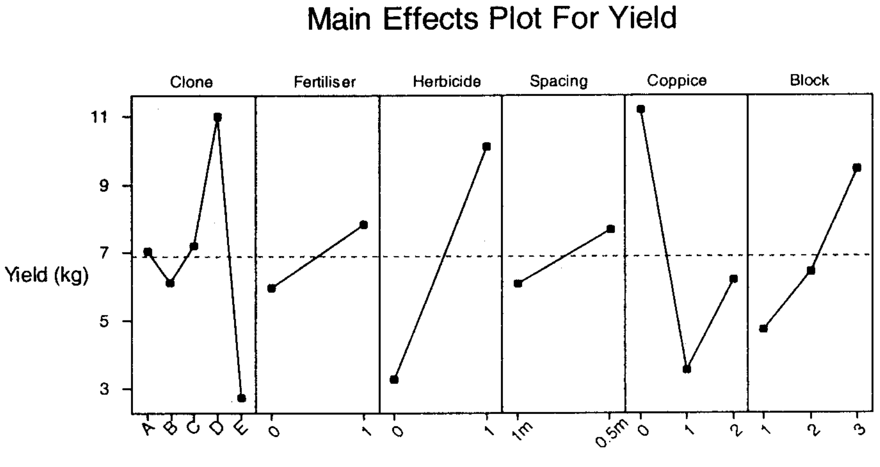


Figure 3.3.9 Plot of the Yield obtained against Clone and Treatment

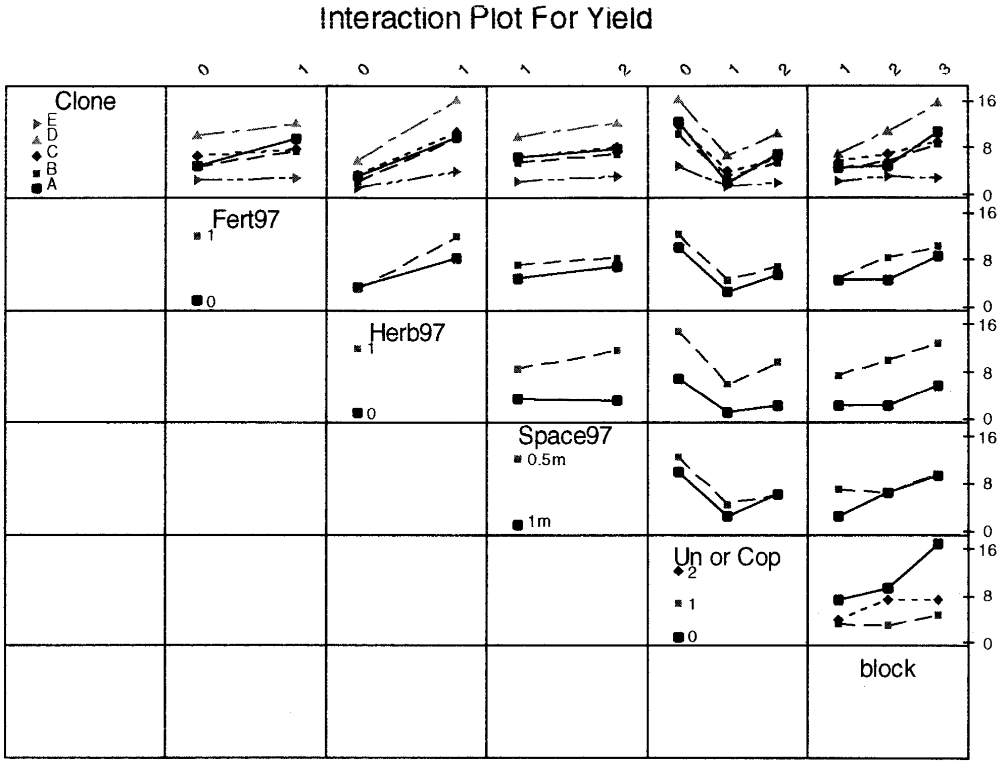


Figure 3.3.10 Plot of the Interactions between Yield and the Various Treatment Combinations

3.3.6 Formal Analysis of the Total Yield over the 3 Years of the Field Trial

Formal determination of the variables which have a significant effect on the yield involved the fitting of a general linear model using only significant main effects and 2-way interactions to avoid over-fitting the model. Due to evidence of non-constant variance a log transformation of the data was undertaken. Table 3.18 provides the results from the general linear model.

Table 3.18 General Linear Model of the Treatment and Clone Effects upon Yield

```
General Linear Model

Factor     Type Levels Values
Clone     fixed      5 1 2 3 4 5
Fert      fixed      2 0 1
Herb      fixed      2 0 1
Space     fixed      2 1 2
Block     fixed      3 1 2 3
Coppice  fixed      3 0 1 2

Analysis of Variance for loge yield, using Adjusted SS for Tests

Source           DF      Seq SS      Adj SS      Adj MS        F       P
Clone             4      66.105      69.673      17.418    19.55   0.000
Fert              1       5.864       3.615       3.615     4.06   0.045
Herb              1     222.598     216.272     216.272   242.75   0.000
Space             1       6.418       6.814       6.814     7.65   0.006
Block             2      44.790      43.179      21.590    24.23   0.000
Coppice           2     134.276     132.284      66.142    74.24   0.000
Fert*Herb         1       8.151       8.362       8.362     9.39   0.002
Herb*Space        1       5.944       6.301       6.301     7.07   0.008
Space*Block       2      32.257      32.257      16.128    18.10   0.000
Error           316     281.531     281.531       0.891
Total           331     807.934

Unusual Observations for loge yield

Obs        C96        Fit   StDev Fit  Residual   St Resid
 26   -2.30259    0.74191     0.21092  -3.04449     -3.31R
 95    2.42569    0.20276     0.20676   2.22292      2.41R
 99   -1.13943    0.79957     0.21515  -1.93900     -2.11R
101   -1.60944    0.63491     0.20973  -2.24434     -2.44R
194   -2.21641   -0.16883     0.20737  -2.04758     -2.22R
244   -0.89649    1.01333     0.20368  -1.90982     -2.07R
248   -2.24432   -0.01442     0.21024  -2.22990     -2.42R
263    3.64545    1.60500     0.20410   2.04045      2.21R
273   -1.61949    0.33319     0.20835  -1.95268     -2.12R
299   -1.89712    0.26382     0.20661  -2.16094     -2.35R
334    0.32136   -1.56022     0.20798   1.88158      2.04R
352   -0.04082    1.81083     0.20350  -1.85166     -2.01R

R denotes an observation with a large standardized residual.
```

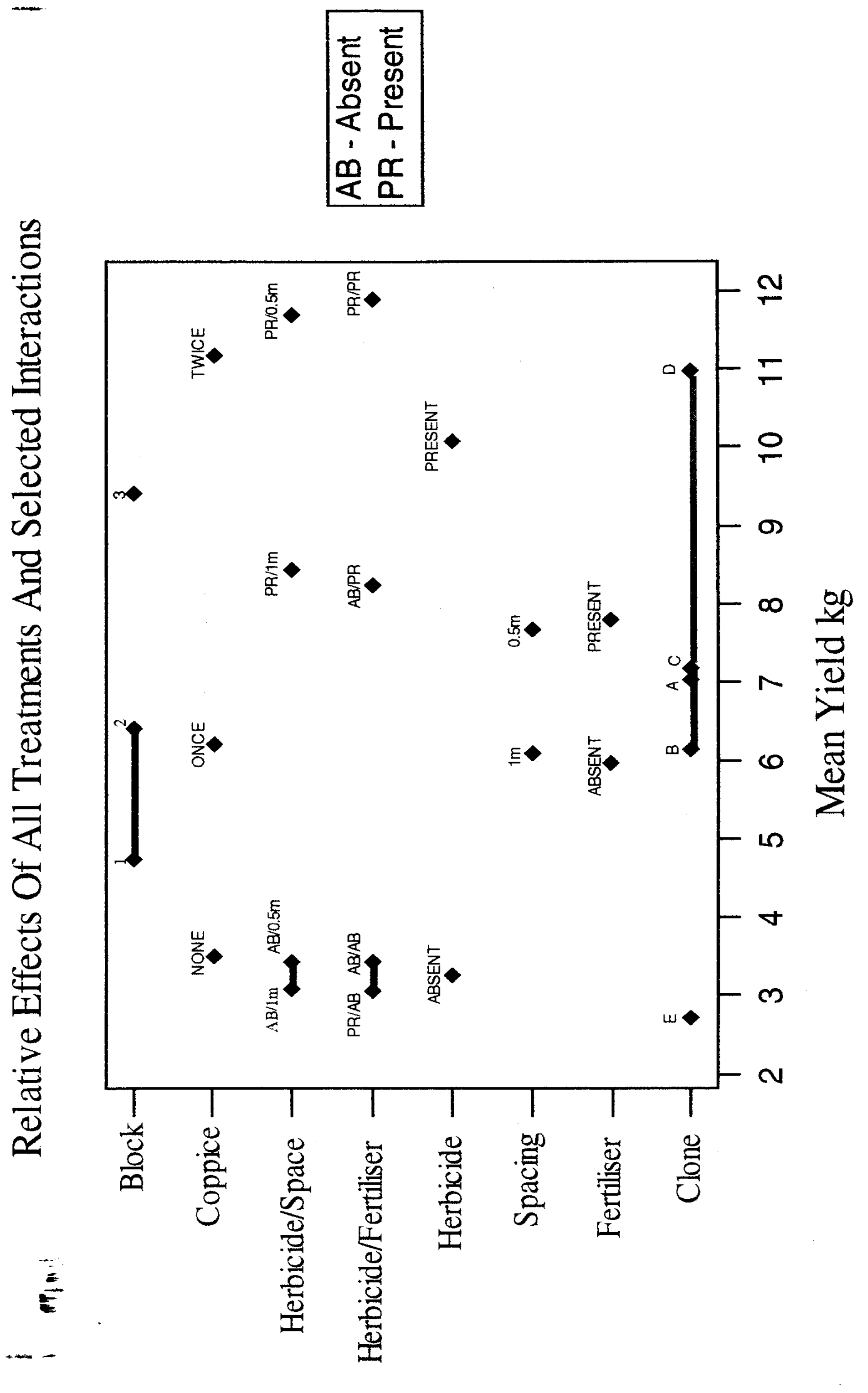


Figure 3.3.11 Plot of the Relative Effects of all Treatments and Clone upon Yield

Figure 3.3.11 shows the results from the multiple comparisons to give an overall impression of the variability of the influence of the treatments and willow clone upon yield. Figure 3.3.12 is the final plot and illustrates the overall survival of the clones by yield and by block.

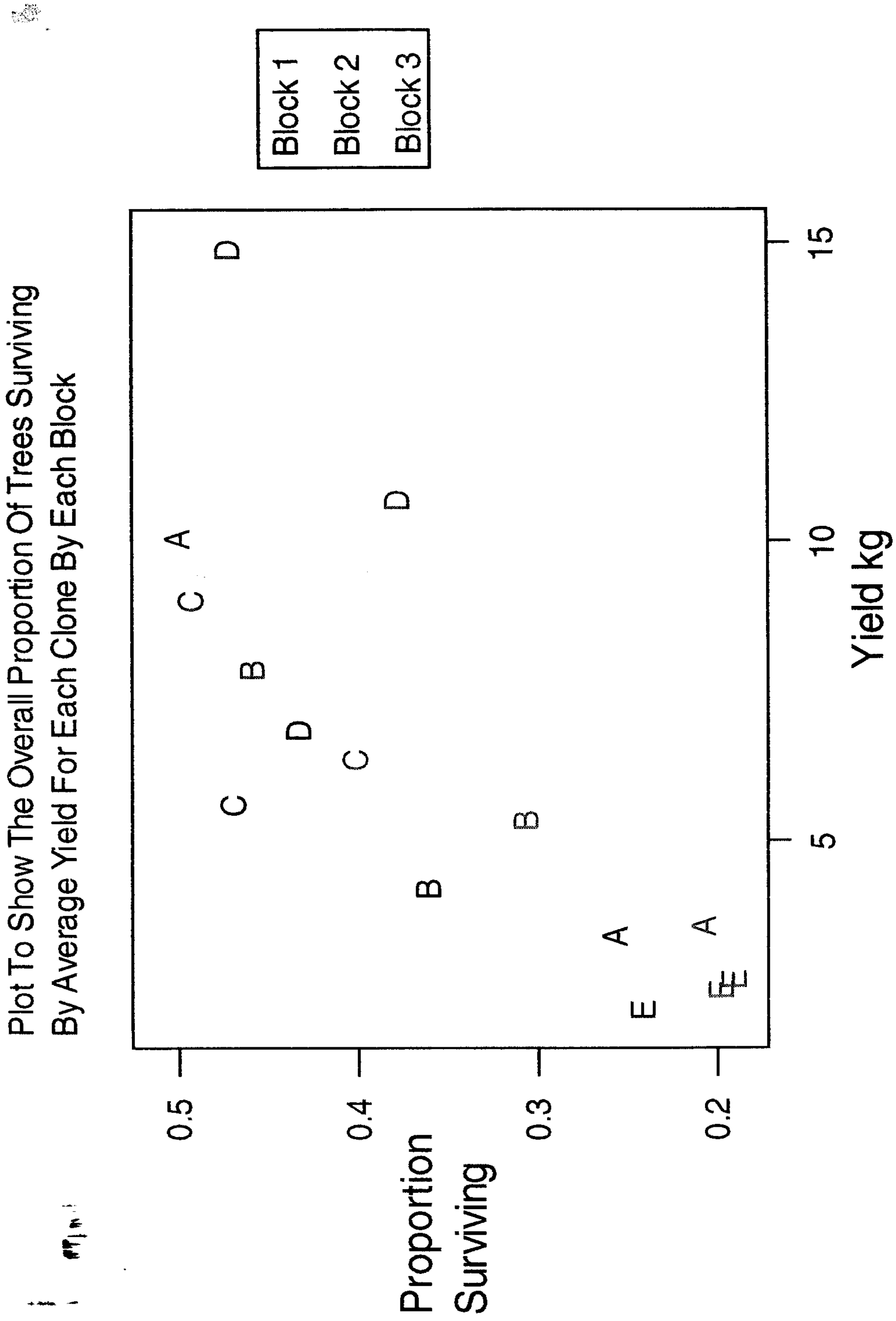


Figure 3.3.12 Plot of the Overall Survival of Individual Clones by Average Yield and Block

3.4 Metal Concentrations in the Biomass Samples

Results obtained following the nitric acid digestion of the ground dried wood and bark materials are reproduced in Table 3.19. Values for lead and chromium have not been reproduced as these were all below the detection limit of the atomic absorption spectrophotometer.

Table 3.19 Metal Concentrations in the Biomass Samples Obtained from those Plots Not Subject To Any Silvicultural Treatments. All results expressed in mg kg $^{-1}$ of air-dried biomass

Sample Id	Zn	Cd	Cu	Ni
4A	145.7	1.0	8.9	1.0
14A	228.5	3.3	15.9	6.0
32A	242.1	2.0	7.9	4.0
37A	172.9	1.0	18.9	4.0
57A	260.7	2.0	18.9	0.0
59A	170.6	1.7	10.9	2.7
4B	120.9	1.3	9.9	8.9
14B	185.6	3.3	18.9	6.0
32B	259.7	1.0	17.9	0.0
37B	270.5	3.0	28.5	2.0
57B	186.4	1.7	15.9	4.7
59B	137.1	1.7	14.9	4.7
4C	151.3	2.0	12.9	4.0
14C	221.1	3.0	55.3	4.3
32C	245.0	0.0	18.9	3.0
37C	166.3	1.0	15.9	1.0
57C	215.8	1.7	13.9	7.7
59C	148.9	1.7	10.9	1.7
4D	143.5	2.0	8.9	4.0
14D	148.6	4.0	14.9	9.3
32D	155.6	0.0	11.9	1.0
37D	151.9	0.0	11.9	0.0
57D	190.9	1.7	9.9	2.7
59D	103.2	1.7	8.9	1.7
4E	157.5	2.0	10.9	4.0
14E	196.0	1.0	6.0	0.0
32E	208.1	2.0	16.9	4.0
37E	127.2	0.0	13.9	3.0
57E	0.0	0.0	0.0	0.0
59E	176.7	1.7	10.9	5.4
Mean	176.3	1.6	14.7	3.4
S.D.	55.5	1.0	9.3	2.6
Max	270.5	4.0	55.3	9.3
Min	0.0	0.0	0.0	0.0
Median	171.7	1.7	13.4	3.5

*Bdl – Below detectable limit

3.4 Additional Clone Assessment

In addition to data gathered from the trial plots, data were collected from approximately 20 other clones of Willow SRC on the site. These clones were planted by the Greenbelt Group Ltd and it had not been possible to exercise any control over the planting regime. Weed control was the only known silvicultural management practice superimposed upon these additional clones.

All sampling and analysis was undertaken in the winter months at the end of the first years growing season. All survival data collected from the tagged lines were taken at intervals of 0-10 m, 20-30 m and 40-50 m and the mean value calculated in an attempt to gain a representative figure of survival rates on this site. All samples collected were returned to the laboratory for weighing and drying. When calculating yields, 5 random stools were harvested in the field with the yield per hectare being calculated in accordance with the survival rates. Where yields are noted as zero, despite survival rates being recorded, the volume of biomass harvested has been negligible. Yield and survival data for the tagged lines are presented in Tables 3.20 and 3.21.

During the months of August and September leaf samples were taken from the 2 areas tagged for additional clone assessment. This was an attempt to assess if there were any changes in metal concentrations in the leaves of the willow clones towards the end of the growth season. This was only a brief experiment and the data for the two months assessed are presented in Tables 3.22 – 3.23.

Tables 3.24 and 3.25 present an analysis of the metal content for the tagged lines after the first year of growth. All analysis of the tagged lines was undertaken after one year's growth only. No further data were collected from these areas of the field trial.

3.4.1 Survival & Yield

Table 3.20 Hallside Field Trial Survival and Yield for the Additional Clones – Station Area

Clone Id	Name	Mean	S.D.	Yield ODT Ha^{-1}
S1	Gigantea	60	26	0.106
S2	Stipularis	27	38	0.027
S3	Orm	33	15	0.039
S4	Rapp	10	0	0.012
S5	Dasyclados	13	12	0.053
S6	Torra	53	23	0.128
S7	Coles	23	12	0.000
S8	Ulv	20	10	0.033
S9	Q83	50	20	0.032
S10	Rosewarne	33	15	0.000
S11	Calodendron	47	21	0.017
S12	Jorunn	87	12	0.337
S13	77699	87	15	0.194
S14	Cambell 3106	80	35	0.424
S15	Spaethi	37	6	0.087
S16	Ninians	37	15	0.000
S17	Candida	57	25	0.075
S18	Delamere	67	32	0.207

All survival values are expressed as percentages

ODT – Oven dried Tonnes

Table 3.21 Hallside Field Trial Survival and Yield for the Additional Clones – Village Area

Clone Id	Name	Mean	S.D.	Yield ODT Ha^{-1}
V1	Q83	83	6	0.146
V2	Calodendron	73	25	0.062
V3	Jorunn	93	6	0.415
V4	Cambell 3106	83	12	0.190
V5	Spaethi	83	12	0.185
V6	Ninians	47	15	0.000
V7	Candida	93	6	0.232
V8	Delamere	100	0	0.211
V9	Torra	83	12	0.048
V10	Bjorn	83	15	0.067
V11	Delamere	93	12	0.039
V12	Gigantea	93	6	0.202
V13	Stipularis	67	23	0.039
V14	Bjorn	90	10	0.041
V15	Orm	73	15	0.073
V16	Rapp	83	6	0.022
V17	Dasyclados	50	17	0.000
V18	Jorr	80	17	0.158
V19	Coles	77	40	0.051
V20	Ulv	80	26	0.103

All survival values are expressed as percentages

ODT – Oven dried Tonnes

3.4.2 Leaf Metal Analysis from Samples Collected in August and September

Table 3.22 Hallside Field Trial – Additional Clones Leaf Metal Analysis for August and September – Station Area

		Zn		Cd		Cu		Ni	
Clone Id	Name	August	September	August	September	August	September	August	September
S1	Gigantea	262	1268.5	1.0	9.3	12.9	15.9	10.6	15.9
S2	Stipularis	342	327.0	1.0	7.0	13.6	8.0	9.3	13.9
S3	Orm	221	ND.	0.0	ND.	8.0	ND.	4.0	ND.
S4	Rapp	494	1035.6	1.3	4.6	8.3	10.9	5.0	9.9
S5	Dasyclados	455	531.6	3.0	6.3	13.9	13.9	5.0	8.0
S6	Torra	517	655.2	4.0	7.0	11.6	10.9	7.3	10.9
S7	Coles	264	665.3	4.3	7.0	10.9	14.2	4.3	10.3
S8	Ulv	399	535.0	3.3	4.0	9.3	10.9	4.6	6.3
S9	Q83	434	1923.7	2.0	16.9	14.6	10.9	2.6	7.0
S10	Rosewarne	801	1135.6	8.0	5.3	14.6	15.9	3.0	8.0
S11	Calodendron	388	656.6	2.3	3.0	9.9	9.9	4.0	5.0
S12	Jorunn	502	692.4	1.0	5.3	8.3	7.0	6.6	0.0
S13	77699	588	1173.7	1.0	9.6	8.6	6.9	10.6	0.0
S14	Cambell 3106	545	866.4	1.0	4.6	10.6	7.6	3.3	0.0
S15	Spaethi	477	777.6	1.3	4.3	7.9	5.3	2.0	0.0
S16	Ninians	308	952.5	1.0	3.3	12.9	9.9	2.0	0.0
S17	Candida	398	492.0	1.0	6.0	9.9	4.0	3.0	0.0
S18	Delamere	673	1031.7	3.6	6.0	12.6	6.0	7.0	0.0
	Mean	448	865.9	2.2	6.4	11.0	9.9	5.2	5.6
	S.D.	148	381.6	1.9	3.3	2.4	3.6	2.8	5.5
	Min	221	327.0	0.0	3.0	7.9	4.0	2.0	0.0
	Max	801	1923.7	8.0	16.9	14.6	15.9	10.6	15.9
	Median	445	777.6	1.3	6.0	10.8	9.9	4.5	6.3

All results expressed in mg kg^{-1}

*ND – No Data

Table 3.23 Hallside Field Trial –Additional Clones Leaf Metal Analysis for August and September – Village Area

		Zn		Cd		Cu		Ni	
Clone Id	Name	August	September	August	September	August	September	August	September
V1	Q83	815.7	1348.2	8.9	13.6	8.0	7.0	2.0	0.0
V2	Calodendron	747.7	1282.8	8.3	8.0	6.9	7.0	1.0	0.0
V3	Jorunn	618.3	1200.4	6.6	9.0	6.0	8.0	3.0	0.0
V4	Cambell 3106	625.7	1134.5	7.0	7.9	8.0	31.8	2.0	0.0
V5	Spaethi	822.3	1582.2	11.6	19.5	7.0	6.0	3.0	0.0
V6	Ninians	474.6	738.9	10.3	9.9	11.9	10.9	8.9	6.0
V7	Candida	253.4	630.7	8.6	18.6	5.0	7.0	6.3	20.9
V8	Delamere	1124.2	2306.2	23.5	32.8	8.9	12.9	10.3	12.9
V9	Torra	987.2	1719.8	14.9	20.2	7.9	11.9	4.0	9.9
V10	Bjorn	1050.3	2054.8	16.9	19.5	6.9	8.9	2.0	8.3
V11	Delamere	1600.7	2196.9	22.8	25.8	9.9	12.9	2.0	10.3
V12	Gigantea	879.0	1351.0	8.9	9.9	7.9	10.9	0.0	7.0
V13	Stipularis	1040.6	1999.4	13.9	20.9	19.9	7.9	22.5	6.0
V14	Bjorn	1237.1	1983.5	12.6	20.2	8.9	13.9	7.0	11.9
V15	Orm	631.3	1139.1	7.3	9.6	6.0	9.9	7.9	8.9
V16	Rapp	632.6	794.8	7.6	7.6	7.9	9.9	5.0	15.6
V17	Dasyclados	553.3	597.8	9.9	8.6	8.9	9.9	11.3	18.6
V18	Jorr	667.0	1139.9	8.6	8.9	7.0	9.9	7.9	11.9
V19	Coles	676.7	685.9	12.3	7.9	44.4	7.0	76.2	11.6
V20	Ulv	844.6	661.4	8.9	5.0	13.9	8.9	15.6	7.9
	Mean	814.1	1327.4	11.5	14.2	10.6	10.6	9.9	8.4
	S.D.	300.8	560.7	4.9	7.5	8.6	5.5	16.6	6.2
	Min	253.4	597.8	6.6	5.0	5.0	6.0	0.0	0.0
	Max	1600.7	2306.2	23.5	32.8	44.4	31.8	76.2	20.9
	Median	781.7	1241.6	9.4	9.9	8.0	9.9	5.6	8.6

All results expressed in mg kg^{-1}

3.4.3 Analysis of the Additional Clones for Metal Uptake in the Wood Tissue

Table 3.24 Hallside Field Trial – Additional Clones Metal Uptake in the Wood Tissue – Station Area

Clone Id	Name	Ni	Zn	Pb	Cu	Cr	Cd
S1	Gigantea	10.9	219.6	3.0	5.3	1.7	2.3
S2	Stipularis	11.3	286.0	0.0	8.6	2.3	4.3
S3	Orm	1.4	167.4	0.0	7.4	2.7	2.2
S4	Rapp	10.2	192.9	7.5	16.3	2.4	2.8
S5	Dasyclados	4.2	252.6	0.8	13.9	3.4	3.8
S6	Torra	9.6	241.2	0.0	9.6	1.3	3.6
S7	Coles	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
S8	Ulv	0.8	197.1	0.0	6.9	0.8	2.0
S9	Q83	1.9	197.3	7.5	12.3	2.1	2.8
S10	Rosewarne	1.5	325.3	0.0	16.4	1.5	5.8
S11	Calodendron	2.2	354.2	0.0	10.5	1.2	6.4
S12	Jorunn	3.6	263.5	0.0	8.3	1.3	3.3
S13	77699	2.1	206.2	0.0	8.0	1.4	2.1
S14	Cambell 3106	2.6	183.8	4.1	9.9	3.1	3.5
S15	Spaethi	5.6	227.8	0.0	7.3	2.7	3.6
S16	Ninians	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
S17	Candida	5.6	204.2	6.3	9.6	0.0	3.6
S18	Delamere	2.2	231.1	0.0	11.5	1.7	3.1
	Mean	4.7	234.4	1.8	10.1	1.8	3.5
	S.D.	3.7	51.7	2.9	3.2	0.9	1.2
	Min	0.8	167.4	0.0	5.3	0.0	2.0
	Max	11.3	354.2	7.5	16.4	3.4	6.4
	Median	3.1	223.7	0.0	9.6	1.7	3.4

All results expressed in mg kg^{-1}

N.D. - No Data

Table 3.25 Hallside Field Trial – Additional Clones Metal Uptake in the Wood Tissue – Village area

Clone Id	Name	Ni	Zn	Pb	Cu	Cr	Cd
V1	Q83	15.2	323.2	3.0	13.6	3.0	8.3
V2	Calodendron	2.2	277.6	17.4	11.6	1.1	5.1
V3	Jorunn	2.0	310.2	0.0	9.2	1.3	6.5
V4	Cambell 3106	10.9	226.9	9.6	7.0	2.3	5.6
V5	Spaethi	0.6	271.6	7.5	11.3	6.0	5.5
V6	Ninians	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
V7	Candida	7.5	248.8	7.5	12.3	3.7	9.4
V8	Delamere	3.1	436.7	0.0	16.9	0.9	12.7
V9	Torra	12.9	367.2	0.0	8.3	2.0	7.6
V10	Bjorn	1.2	395.9	0.0	9.6	1.0	8.8
V11	Delamere	4.6	448.8	7.5	14.6	1.4	10.8
V12	Gigantea	0.0	265.6	0.8	8.9	1.4	4.5
V13	Stipularis	2.9	438.5	7.5	10.6	1.7	9.4
V14	Bjorn	5.6	570.4	17.4	13.9	1.7	9.4
V15	Orm	1.4	321.8	7.0	12.5	0.9	6.7
V16	Rapp	11.6	456.7	0.0	9.0	1.7	9.3
V17	Dasyclados	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
V18	Jorr	0.7	267.0	0.0	9.3	0.7	6.6
V19	Coles	4.8	196.9	0.0	9.9	1.7	4.7
V20	Ulv	3.6	446.3	7.5	18.3	3.7	7.5
	Mean	5.1	348.3	5.1	11.5	2.0	7.7
	S.D.	4.7	101.2	5.7	3.0	1.3	2.3
	Min	0.0	196.9	0.0	7.0	0.7	4.5
	Max	15.2	570.4	17.4	18.3	6.0	12.7
	Median	3.3	322.5	5.0	10.9	1.7	7.6

All results expressed in mg kg^{-1}

N.D. - No Data

CHAPTER 4 - DISCUSSION

4.1 Plant Growth Data Analysis

Statistical analysis of the data that was collected during this study was limited to some degree due to the low survival rates of the willow stools, which undoubtedly affected all the other parameters measured. Mean values were used to represent the data collected from the field. At best, this would have been a mean value for 5 stools randomly selected and measured within a treatment plot. However, it should be noted that where survival is low this may comprise a single surviving stool.

For the stools surviving, observed variations in growth parameters were high, and in consultation with the Department of Statistics at the University of Glasgow these variations were noted as representing limitations on the quality of statistics produced, particularly where the survival rates were low as the measurement of the surviving stool(s) might not always give an accurate picture of the effect of the silvicultural treatments upon the plot.

Results from the field trial, as presented in Chapter 3, are initially presented here as histograms to show the effects of the treatments upon the individual measured parameters, namely survival, height, diameter, number of shoots and yield. At best these histograms can be used to show general trends. Statistical interpretation is subsequently made to consider the significance of these trends upon survival and yield as these were deemed to be the most important factors to be influenced by the treatments.

4.1.1 Analysis of the Survival, Heights, Diameters, Number of Shoots and Yields for Individual Clones within the Treatment Plots

Initial presentation of the gathered data by a series of histograms showing the impact of the treatments upon survival rates, heights, diameters, number of shoots and yields are presented in Figures 3.2.1 – 3.2.48.

(i) Survival Rates

Subjective analysis of the survival data, when viewed against plot treatments for the three years, seemed to suggest that different survival rates were apparent. In general, the addition of fertiliser on its own seems to demonstrate little effect upon the survival of the clones, however when the interactions with the other treatments, notably herbicide are considered, survival rates increase. The effect of fertiliser upon the survival of clones in general seems to be more pronounced when fertiliser has been used in conjunction with herbicide; that is, there is an adverse effect on survival when fertiliser alone is used. Where fertiliser was used without herbicide, survival rates were generally low, with stools planted at the higher densities (0.5 m spacing) demonstrating some of the lowest of all survival rates.

Some difficulties were experienced in recording the survival of the willow due to either weeds hiding the stools in the first year or difficulties at plot edges in determining the exact plot boundaries. The main consequence of this was that survival rates in some instances appeared to increase over the three year period. As no additional planting was undertaken to replace dead stools this could not have proved possible. Survival results collected in the final year are considered to be the most accurate of all survival rates recorded.

Clone E (Spaethii) demonstrated itself to be the clone with the poorest survival rate. However, when its survival is viewed where fertiliser has been added and when planted at 0.5 m spacing, the survival rates did not show as marked a difference as when compared against other treatments.

The use of herbicide in increasing the survival rates was clearly visible in Figures 3.2.1 – 3.2.6. The presence of herbicide increases survival rates when compared against those plots where no herbicide was used. When assessed against the other treatment parameters, plots with the addition of herbicide and fertiliser clearly outperformed those treatments with no fertiliser, however the degree of difference when assessed against those plots that have received herbicide but no fertiliser is small.

The recorded differences between those clones planted at 0.5 m or 1.0 m planting densities are only marked when herbicide has been used. The addition of fertiliser but no herbicide seems to result in poorer recorded survival rates (apart from clone E (Spaethii)) for all clones.

The survival of all clones when assessed against the rotation length or the year that the clone was first coppiced show that for those clones coppiced in the first or second year survival rates decreased where no herbicide was used. As has already been noted, those clones receiving the herbicide treatment clearly exhibit higher survival rates. The influence of the other treatments is less noticeable on their own however, in combination with herbicide, an increased survival rate is apparent. Clone spacing survival rates seem to indicate that the lowest density of planting has at all times out performed those planted at 0.5 m spacing, both with and without the addition of herbicide.

Figure 3.2.6 represents a visual representation of proportions surviving over the three years of the field trial. Both figures, when summed up, indicated that the individual clones had both variable and low overall survival rates, particularly in comparison to similar data for willow established on agricultural land (Dawson, Personal Communication). In order of ranking, Clones C (Dasyclados) and D (Gigantea) exhibited the greatest survival followed in order by Clones B (Burjatica Germany), A (Rosewarne White) and E (Spaethii).

Survival results presented in the survival histograms when compared to the plots of the proportion of stools surviving (Figures 3.3.3 and 3.3.6) are similar and confirm the variability of the survival rates at the field trial. Interpretation of the survival data for the plots would suggest that –

- The addition of fertiliser alone does not make increase survival rates but adding fertiliser in the presence of herbicide appears to increase the survival for both planting densities

- When herbicide is not used the survival appears slightly higher for the 1 m planting density compared to 0.5 m density
- When herbicide is used the survival appears slightly higher for the 1 m planting density than when fertiliser is not used
- A blocking effect is apparent across the three trial blocks with higher survival rates being apparent for block 3, than for blocks 1 and 2. This is particularly apparent when herbicide is not used. While block 3 appears to have higher survival values, values in blocks 1 and 2 seem to be similar.
- Not coppicing the stools in years 1 and 2 would suggest that a higher proportion of the trees survive compared to those that are coppiced after the first and second year's growth.

(ii) Heights

Recorded heights at the end of each growing season clearly indicate that year on year the average heights attained by individual clones have increased. The recording of heights in itself has not been undertaken to predict yields but to consider whether individual clones can demonstrate an ability to out compete weed growth in the absence of herbicide treatment (a potential benefit on a derelict and contaminated site where the use of herbicide could be viewed as an expensive management tool, particularly if not always effective)

The order of the clones when assessed against heights clearly shows Clone D (Gigantea) to be the best performing with Clone E (Spaethii) being the worst. The ranking of the remaining clones was assessed as Clone C (Dasyclados) being the next tallest to Clone D (Gigantea) followed by Clone B (Burjatica Germany) then A (Rosewarne White). This picture in itself is however misleading as it fails to take into account the variations that exist between treatments and clones. Gigantea is a tall growing clone as the name suggests, this clone is known for its height whilst Rosewarne White and Dasyclados have a tendency to be small and stockier. As would be expected those clones that have been allowed to grow uncoppiced for three years clearly attain the greatest heights.

When average heights attained are assessed against the treatments received, in general, fertiliser has no substantial or significant effect on the final height of the willow clones. Herbicide on the other hand has a noticeable effect on the final height of the willow clones, this is assumed to be because of the reduction in completion from weeds as a result of its use This is best illustrated in Figure 4.1.1

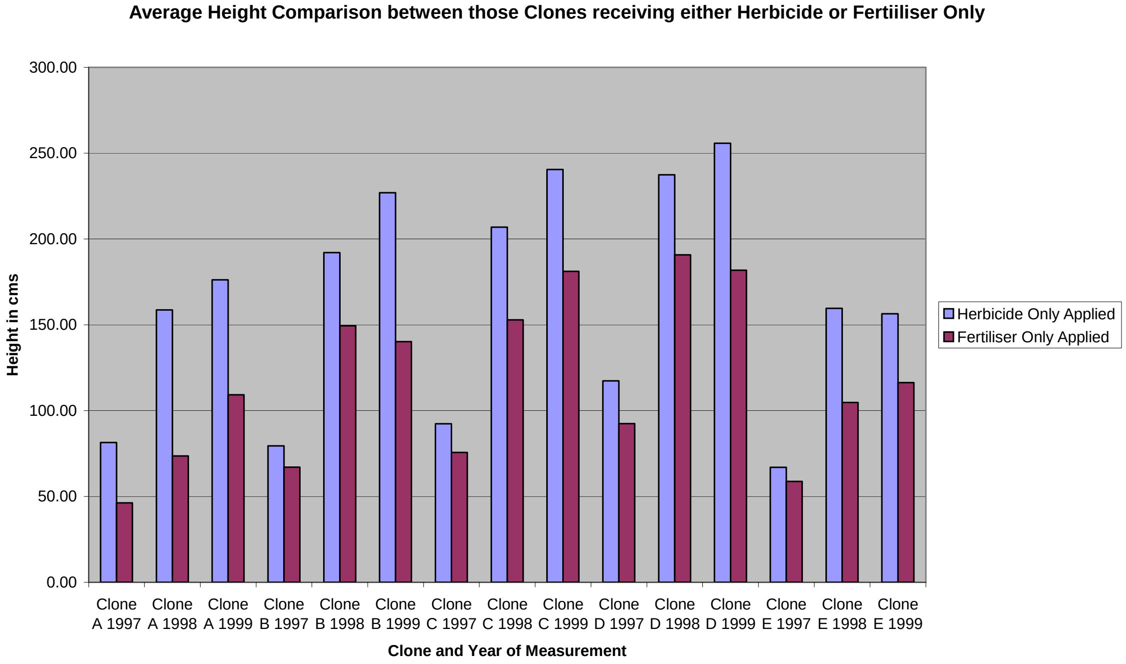


Figure 4.1.1 Average Height Comparison between those Clones Receiving either Herbicide or Fertiliser Only

However, the patterns that have emerged are not as straightforward as to consider the use of fertiliser and herbicide as being beneficial to the heights attained by individual clones. The benefits of utilising herbicide have already been noted; however, what also becomes apparent is that the use of fertiliser in conjunction with herbicide has benefits. Where herbicide is not used, the greatest heights were attained in those treatment plots that also did not receive any fertiliser. The use of fertiliser where herbicide application is absent seemed to indicate a reduced average height, negating any benefit that might have been derived from the fertiliser. It is assumed that the competitive effects of increased weed growth due to fertiliser application account for this (See Figure 4.1.2).

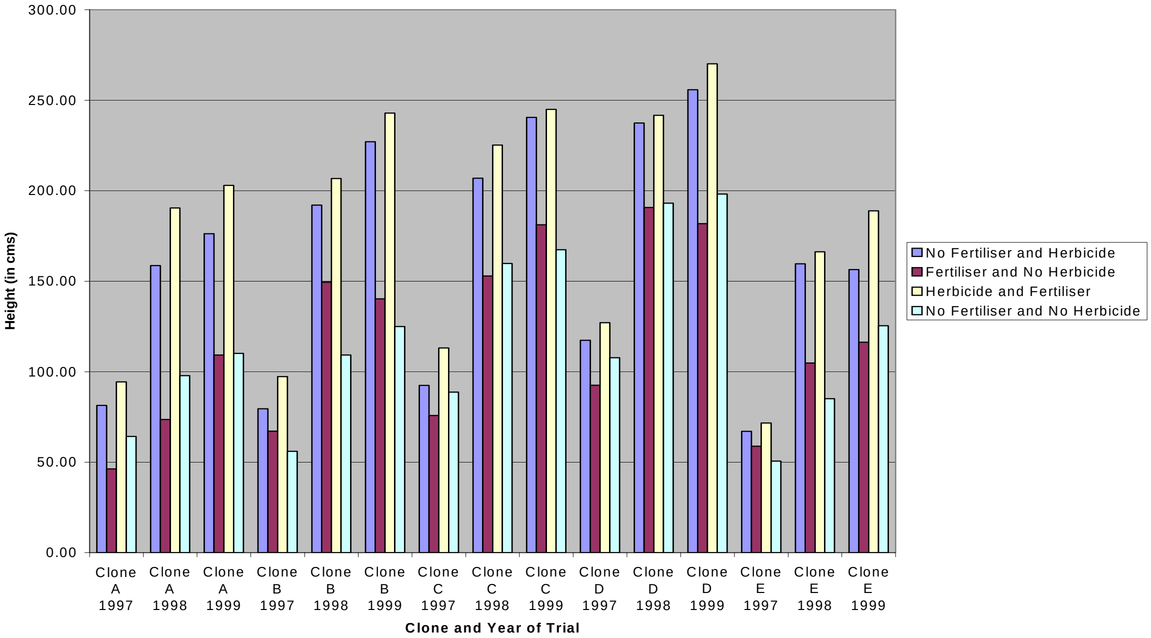


Figure 4.1.2 Average Heights of All Clones Against the Effect of Fertiliser and Herbicide Treatments

Spacing on its own does not exhibit any significant effect upon the final height of the willow clones. When considering all possible herbicide/ fertiliser and spacing combinations, Clone D (Gigantea) on the whole out performs all other clones followed by Clone C (Dasyclados). Clone E (Spaethii) is consistently the worst clone for most treatments. This is best illustrated in Figure 3.2.12 which shows the average heights recorded for all clones in 1999 only.

(iii) Diameters

Recorded diameters for all clones were assessed against individual treatments and as would be expected annual average diameters increased as rotation length increased.

In general terms the effect of all the treatments clearly indicate that Clone D (Gigantea) and C to be the best in terms of diameter size with Clone E (Spaethii) the worst, however the combination of treatments is not as straight-forward. Plots treated with herbicide seem to give the best all round average diameters. If the effects of fertiliser and herbicide combinations are taken into consideration as is indicated in Figure 4.1.3, then clearly the benefits of using herbicide and fertiliser are obvious, however where no herbicide is used the average diameters are greater if no fertiliser is applied.

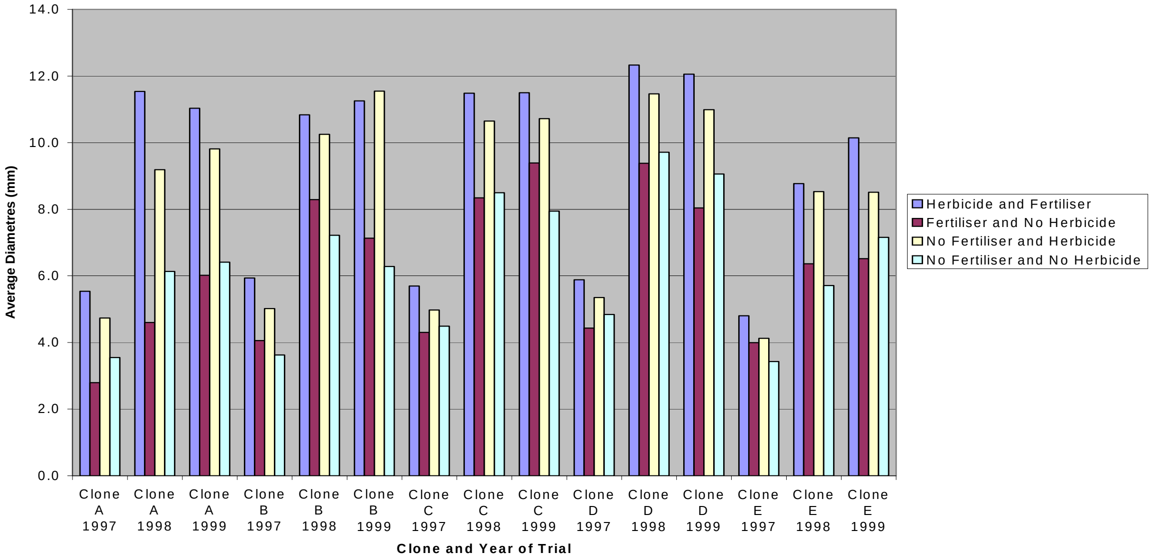


Figure 4.1.3 Average Diameters of All Clones Against the Effect of Fertiliser and Herbicide Treatments

Where neither fertiliser or herbicide is applied and where fertiliser is applied to plots in the absence of herbicide, the results suggest that average stool diameters were less. It is suggested that with the reduction in competition from the use of herbicides, diameters increase. Where weed competition is increased with the use of fertiliser, in the absence of weed control, growth is at its poorest. This is likely to be of greater impact where poor survival is recorded, as this will allow weed development due to the failure of the coppice system to ensure canopy closure.

(iv) Number of Shoots

Assessing the number of shoots produced by individual clones was undertaken to consider the effect of coppicing upon biomass production. When an average number of shoots was calculated against all treatments, no individual Clone E (Spaethii) merged as producing more shoots than others.

When the number of shoots is considered against the year of coppicing, a clearer picture emerges (see Figure 4.1.4). The number of shoots produced is greater for those clones coppiced in year 2 than those coppiced annually. Clone D (Gigantea) produces the greatest number of shoots followed by B (Burjatica Germany) and A (Rosewarne White). Clone C (Dasyclados) and E (Spaethii) both produce the least number of shoots. The values indicated for those stools coppiced in year 3 below represent the number of shoots recorded prior to coppicing, no record has been obtained for the number of shoots produced for the year following the coppice of 3 year old stools.

Dawson (Personal Communication, 2003) has indicated that the above scenario is opposite to what would be predicted in an agricultural willow plantation with stools harvested annually producing a larger number of shoots which diminish in years 2 and 3 as they lose out to competition. Experience gained from this field trial would suggest that those stools coppiced in year 2 produce a far greater number of shoots. It may be presumed that coppicing willow on disturbed and contaminated sites after the first year's growth may be too early, affecting both the survival and growth of the willow. Allowing the stools to grow for 2 years prior to coppicing may be an appropriate measure to ensure their effective survival and establishment in such poor growing mediums.

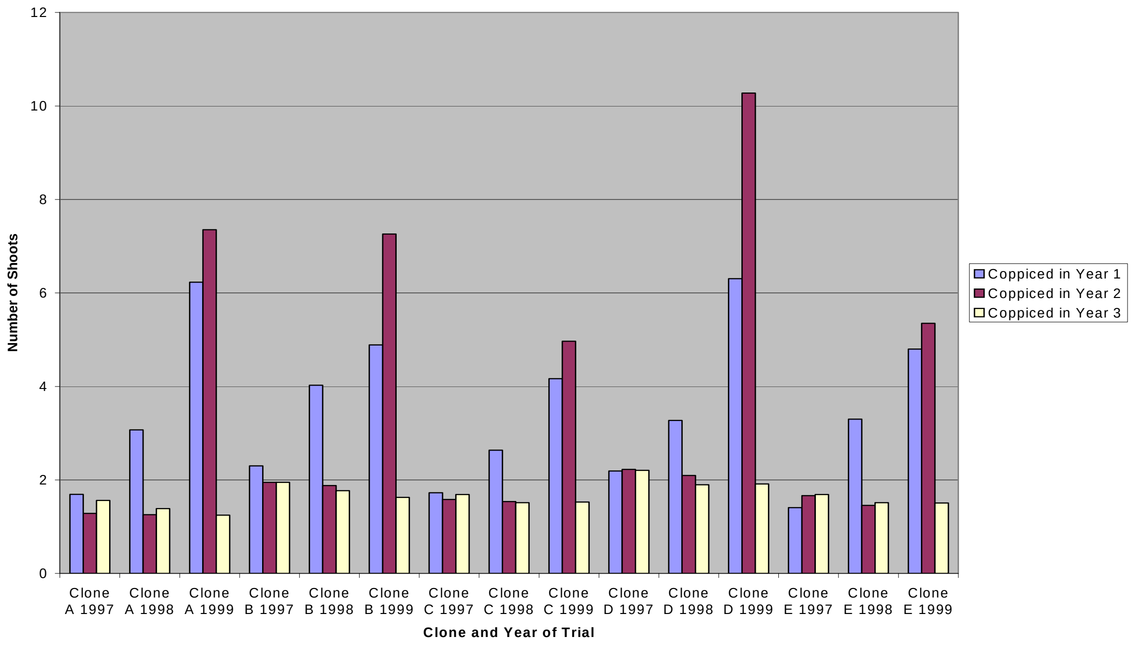


Figure 4.1.4 Average Number of Shoots Recorded Against Year of Coppicing in 1999

An assessment of the number of shoots produced against the effect of both fertiliser and herbicide (see Figure 4.1.5) would suggest the importance of herbicide and fertiliser in the number of shoots produced by individual clones. In order of ranking, Clone D (Gigantea) produces the greatest number of shoots as a consequence of herbicide and fertiliser application, followed by B (Burjatica Germany) and A (Rosewarne White). Clones C (Dasyclados) and E (Spaethii) both produce the least number of shoots as a consequence of the herbicide and fertiliser treatments.

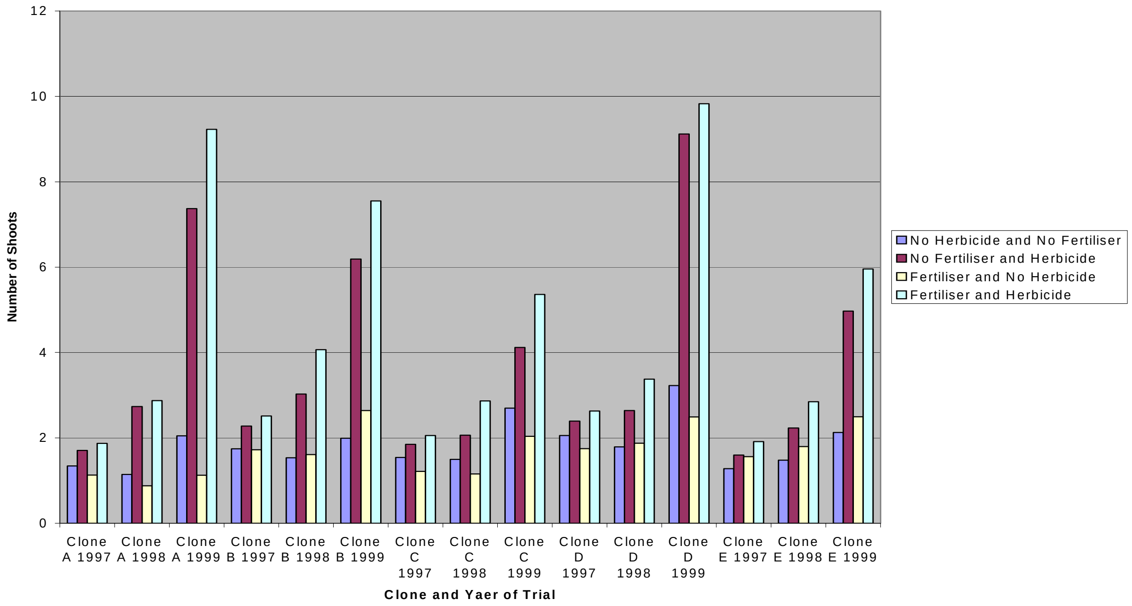


Figure 4.1.5 Average Number of Shoots Produced Against the Effect of Fertiliser and Herbicide Treatments

The effect of fertiliser and herbicide additions upon the number of shoots produced is noticeable, however these values are closely mirrored by the results for those plots that have received herbicide and no fertiliser, having values only marginally less. Most but not all results also indicate that where there has been an addition of fertiliser without the use of herbicide the number of shoots were less than those for where no herbicide or fertiliser was applied. As has been noted in the assessment of heights, this is considered to be as a consequence of the influence of weed competition resulting from a failure of the willow to reach canopy closure.

(v) Yields

Year 1

Yields in oven dry tonnes were calculated for each year of the field trial following the harvest of selected plots. The results (Figure 3.2.25 – 3.2.30) for all plots harvested in the first year, i.e. only those plots having a 1 year rotation length, indicated that Clone D (Gigantea) yielded the greatest harvest, followed by Clone B (Burjatica Germany) and Clone C (Dasyclados) with Clone E (Spaethii) recording the lowest yield.

When average yields for all treatments are evaluated against spacing it would be expected that those clones planted at double density would exhibit double the yield. Whilst this is apparent for nearly all the clones in Table 4.1, the picture is somewhat misleading as it fails to take into account fully the effects of the other treatments.

Table 4.1 Average Yield for All Treatments Against Spacing (all results are expressed in oven dry tonnes per hectare)

	Clone A	Clone B	Clone C	Clone D	Clone E
0.5m Spacing	0.160	0.366	0.386	0.490	0.120
1.0m Spacing	0.153	0.167	0.117	0.267	0.073

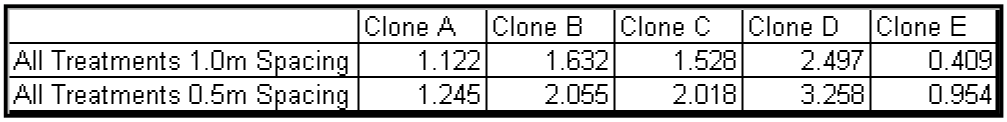
As Figure 3.2.26 - 3.2.28 in the previous chapter clearly demonstrates, the yields for Clones C (Dasyclados), B (Burjatica Germany) and D (Gigantea) planted at 0.5 m spacing and receiving both herbicide and fertiliser are approximately double those planted at 1.0 m spacing and receiving the same treatments.

Year 2

Recorded yields for the second harvest (Figures 3.2.31 – 3.2.36) indicated that Clone D (Gigantea) produced the greatest yield of all the clones followed by Clones B (Burjatica Germany), C (Dasyclados) and A (Rosewarne White) with Clone E (Spaethii) providing the lowest yield.

The effect of planting density was not as pronounced as for the 1 year rotation. In the first year’s harvest, most clones produced double the volume of biomass when planted at the greater density. Table 4.2 provides the yields of the second year's harvest. Whilst all double density planting produced greater yields than for those clones planted at single density, these values have only been doubled for Clone E (Spaethii), the poorest yielding clone. Clone A (Rosewarne White) has produced a comparable biomass yield for both planting densities, whilst Clones B (Burjatica Germany), C (Dasyclados) and D (Gigantea) produce between 25-32% greater biomass at the double planting density.

Table 4.2 Average Yield Against All Treatments for 1.0 m and 0.5 m Spacing (all results are expressed in oven dry tonnes per hectare)



	Clone A	Clone B	Clone C	Clone D	Clone E
All Treatments 1.0m Spacing	1.122	1.632	1.528	2.497	0.409
All Treatments 0.5m Spacing	1.245	2.055	2.018	3.258	0.954

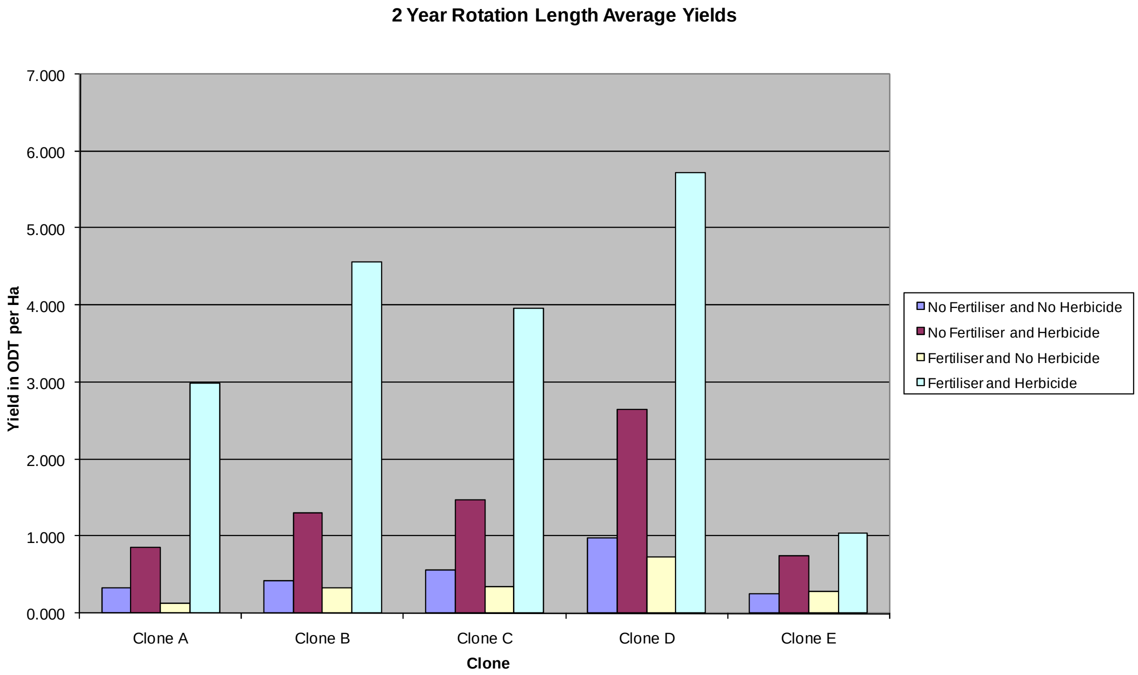
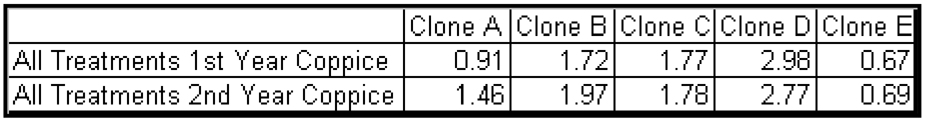


Figure 4.1.6 Second Year Harvest Average Yields - Effect of Fertiliser and Herbicide Treatments

The effect of the herbicide and fertiliser treatments upon yields is shown in Figure 4.1.6. Once again, the effect of herbicide upon biomass yields is clearly demonstrated. Clones receiving herbicide even in the absence of fertiliser produce the second highest levels of yields for all clones whilst clones receiving fertiliser but no herbicide provide the worst yields for all clones. Not surprisingly these yield values mirror the individual growth data parameters, both are products of one another.

The effect of coppicing in the first year is clearly demonstrated in Table 4.3. Yields for those clones harvested in the second year shows that Clone D (Gigantea) coppiced after one years growth, produces a greater average yield as opposed to its total average yield if left uncoppoiced for two years i.e one year of growth following copping yields a greater biomass return than for a stool left uncoppiced and allowed to grow for two years. Clone D (Gigantea)Yields for Clone C (Dasyclados), B (Burjatica Germany) and E (Spaethii) subject to a first year coppice do not exceed those yield values obtained for those clones only coppiced for the first time in the second year, however the values are only marginally lower. Clone A (Rosewarne White) is the only clone to produce significantly less yield after coppicing in the first year, producing approximately 60% less biomass than is measured for the same Clone C (Dasyclados) coppiced in year 2.

Table 4.3 Average Yields For Second Year Harvest of Selected Plots Against All Treatments for Year of Coppicing (all results are expressed in oven dry tonnes per hectare)



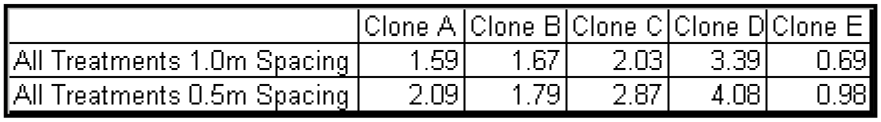
	Clone A	Clone B	Clone C	Clone D	Clone E
All Treatments 1st Year Coppice	0.91	1.72	1.77	2.98	0.67
All Treatments 2nd Year Coppice	1.46	1.97	1.78	2.77	0.69

Year 3

Average yields against all treatments (Figures 3.2.37 – 3.2.42) again showed Clone D (Gigantea) as producing the greatest biomass yield, followed by Clone C (Dasyclados), A (Rosewarne White) and B (Burjatica Germany). Clone E (Spaethii) again proved to be the worst producing Clone.

When yields for the third year's harvest (Table 4.4) were assessed against planting densities, results indicated that all 1.0 m planting centres produced an average yield less than that obtained for those clones planted at 0.5 m centres, with Clone producing 31% less, Clone B (Burjatica Germany) 7% less, Clone C (Dasyclados) 41% less, Clone D (Gigantea) 20% less and Clone 42% less.

Table 4.4 Average Yields for Third Year's Harvest Against all Treatments for 1.0 m and 0.5 m Spacing (all results are expressed in oven dry tonnes per hectare)

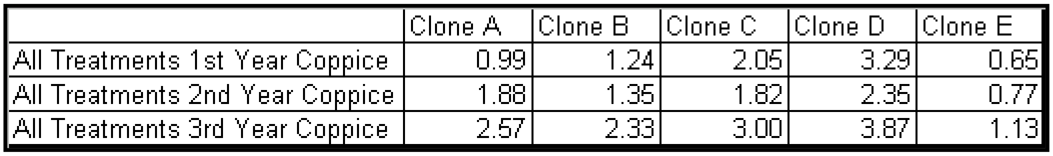


	Clone A	Clone B	Clone C	Clone D	Clone E
All Treatments 1.0m Spacing	1.59	1.67	2.03	3.39	0.69
All Treatments 0.5m Spacing	2.09	1.79	2.87	4.08	0.98

The effect of fertiliser and herbicide has again produced similar results as already discussed for both first and second year harvests.

The effect of coppicing upon yields obtained for those stools first coppiced in year 1 and year 2 (see Table 4.5) indicated that Clones C and D produce the greater yields when coppiced on an annual basis. It might be expected that those clones that had been permitted to grow for 2 years before their first coppice might have exhibited a greater yield from year 2 compared to the harvest in year 3, however the only clone exhibiting increased yield from 1 years growth as a result of being coppiced in year 2 is Clone A (Rosewarne White).

Table 4.5 Average Yields for Third Year Harvest Against all Treatments for Year of First Coppice (all results are expressed in Oven dry tonnes per hectare)



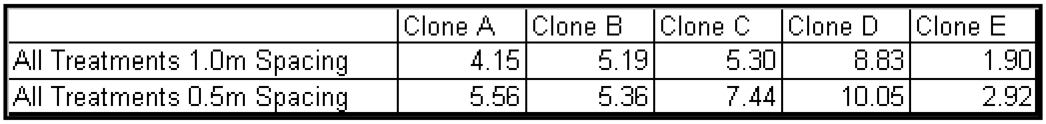
	Clone A	Clone B	Clone C	Clone D	Clone E
All Treatments 1st Year Coppice	0.99	1.24	2.05	3.29	0.65
All Treatments 2nd Year Coppice	1.88	1.35	1.82	2.35	0.77
All Treatments 3rd Year Coppice	2.57	2.33	3.00	3.87	1.13

Cumulative Yield Totals

Average cumulative yield totals i.e. the total yield of 3 years growth was calculated against all treatments. Figures 3.2.43 – 3.2.48 indicated that the clone yield ranking in descending order to be Clone D (Gigantea), Clone C (Dasyclados), Clone B (Burjatica Germany), Clone A (Rosewarne White) and Clone E (Spaethii).

Table 4.6 gives the cumulative results for yield values assessed against planting density and shows that whilst all clones planted at 0.5 m densities produce greater cumulative yields, the increased yield is not double as might be expected. Clones B (Burjatica Germany) and D only produce an additional 3 and 13% yield, respectively, for the 0.5 m planting density. Clone E (Spaethii) shows a 53% increase between planting densities whilst Clones A (Rosewarne White) and C (Dasyclados) range between 33 and 39%.

Table 4.6 Cumulative Yields Against all Treatments for 1.0 m and 0.5 m Spacing Treatments (all results are expressed in oven dry tonnes per hectare)



	Clone A	Clone B	Clone C	Clone D	Clone E
All Treatments 1.0m Spacing	4.15	5.19	5.30	8.83	1.90
All Treatments 0.5m Spacing	5.56	5.36	7.44	10.05	2.92

The cumulative yields seem to indicate what has been apparent throughout this chapter (see Figure 4.1.7) that the over-riding treatment with the most significant effect upon the clones planted in this field trail has been the use of herbicide. Fertiliser whilst having an impact when used in conjunction with herbicide would require its benefits to be assessed carefully to consider whether the cost benefits of its use would outweigh the resultant increase in yield.

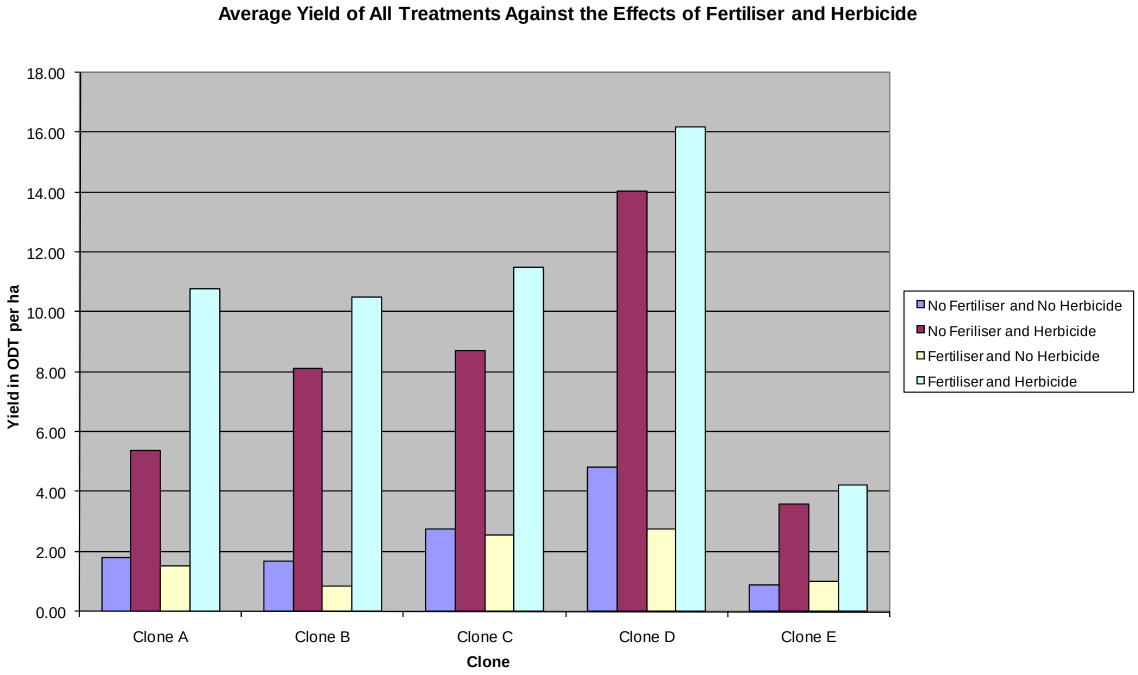
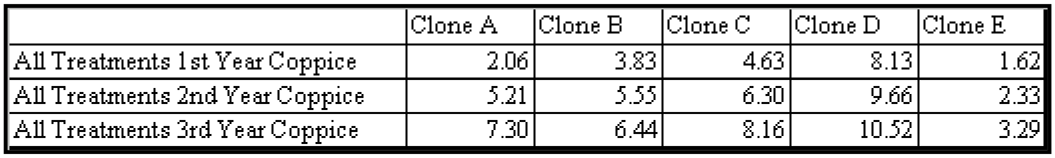


Figure 4.1.7 Average Cumulative Yields Against the Effect of Fertiliser and Herbicide Treatments

Average cumulative yield values when observed against the year of the first coppice indicate that the cumulative biomass yield for all clones to be greatest for the 3rd year coppice. Coppicing in year 1 and year 2 has not, as might have been expected, produced cumulative values greater than for 3 years uninterrupted growth. However, when the yields are assessed across the clones, the margin of difference is less than 30% for Clone D (Gigantea) i.e. the effect of an annual coppice as opposed to 3 years uninterrupted growth produces approximately 23% less biomass. Reduced yields as a consequence of annual coppicing against a three year growth cycle for all other clones ranged from 41-72%. These results are further illustrated in Table 4.7.

Table 4.7 Average Cumulative Yields Against all Treatments for Year of First Coppice (all results are expressed in Oven dry tonnes per hectare)



	Clone A	Clone B	Clone C	Clone D	Clone E
All Treatments 1st Year Coppice	2.06	3.83	4.63	8.13	1.62
All Treatments 2nd Year Coppice	5.21	5.55	6.30	9.66	2.33
All Treatments 3rd Year Coppice	7.30	6.44	8.16	10.52	3.29

Figures 3.3.9 and 3.3.10 may be used to summarise the main effects of the treatments upon yield. These are as follows –

- Differences in yield between clones A (Rosewarne White), B (Burjatica Germany), and C (Dasyclados) are small. Clone D (Gigantea) produced the highest yield and Clone E (Spaethii) the lowest
- The use of fertiliser only increased the yield when herbicide was also usedThe use of herbicide strongly increased yield
- 0.5 m spacing slightly increased yields
- Block 3 produces higher yields than block 1 and 2
- Not coppicing increases yields

4.1.2 Statistical Interpretation of the Survival of the Survival in the First Year

Regression modelling of the survival data (Table 3.7) and the use of odds ratios (Figure 3.3.4) for the first year survival data confirmed the presence of a blocking effect. Whilst there was no practical or obvious reason why the results should be consistent across the three blocks, such inconsistencies may be viewed as an inherent factor of disturbed and contaminated sites.

Significant results produced by the binary logistic regressions fitted individually for each block can be summarised as follows –

Block 1

- The use of fertiliser and a planting density of 0.5 m decreases the chance of survival compared to any other combination of these two variables
- The use of fertiliser and herbicide together with the 0.5 m spacing increases the chance of survival compared to any other combination of these treatments

Block 2

- The use of fertiliser increases the chance of survival compared to not using fertiliser
- The use of herbicide strongly increases the chance of survival when compared to not using herbicide
- Willow planted at 0.5 m spacing increases the chance of survival compared to those planted at 1 m centres
- The use of herbicide reduces the chance of survival of Clone B (Burjatica Germany), C (Dasyclados), and D (Gigantea) compared to its use with Clone A (Rosewarne White)
- The use of herbicide with stools planted at 0.5 m densities decreases the chance of survival compared to any other combination of these two treatments

Block 3

- The use of fertiliser decreases the chance of survival compared to using herbicide
- Willow stools planted at 0.5 m densities decrease the chance of survival compared to those planted at 1.0 m centres
- Clone E (Spaethii)planting at a density of 0.5 m increases Clone E’s (Spaethii) chance of survival compared to Clone A (Rosewarne White) planted at 0.5 m
- The use of fertiliser and herbicide increases the chance of survival compared to any other combination of these two treatments
- The use of herbicide on stools planted at 0.5 m spacing increases the chance of survival compared to any other combination of these treatments

- Clone E (Spaethii) with herbicide present at 0.5 m planting density reduces the chance of its survival when compared to Clone A (Rosewarne White) planted at the same density and with herbicide present

Generally, across all three blocks the odds ratios (Figure 3.3.4 and Table 3.9) indicated a trend for both clones C (Dasyclados) and D (Gigantea) to show the highest chance of survival, whilst clones A (Rosewarne White) and E (Spaethii) performed the worst. The only exception to these findings was for block 3 which dramatically increases the chance of survival for Clone A (Rosewarne White). Block 2 produces a higher odds ratio for Clone D (Gigantea) than block 1, and block 3 produces the highest odds ratios for clones B (Burjatica Germany), C (Dasyclados), A (Rosewarne White and D (Gigantea). Other trends to be noted include the influence of herbicide in increasing survival, little apparent difference in survival rates for the two planting densities when herbicide is present and the small increase in survival rates when fertiliser is used in the presence of herbicide.

4.1.3 Statistical Interpretation of the Survival of the Survival over the Three Years

Initial regression modelling of results from all three blocks combined (Table 3.13) displayed similar results as for the regression model for survival in year 1 only. As noted previously, a blocking effect was apparent which indicated that the 3 blocks increased or decreased the chance of clone survival. Block 2 showed reduced survival rates in comparison to block 1, with block 3 showing increased survival rates. Clone/block interaction showed that Clone A (Rosewarne White) had increased chances of surviving in block 3 compared to the other clones. Similar results were also recorded in the first year analysis.

Significant results produced by the binary logistic regressions fitted individually for each block for the survival rates over the three years can be summarised as follows –

Block 1

- Coppicing the trees annually decreases the chance of survival when compared to not coppicing the trees
- The use of herbicide increases the chance of survival compared to not using herbicide
- Stools coppiced annually at 0.5 m spacing increases the chance of survival compared to stools at the same spacing not coppiced

Block 2

- The use of fertiliser increases the chance of survival compared to not using fertiliser
- The use of herbicide strongly increases the chance of survival compared to not using herbicide
- Stools coppiced annually had reduced chances of survival compared to those not coppiced
- The use of herbicide with stools coppiced once or twice increases the chance of survival when compared to using herbicide with no coppicing
- Clones C (Dasyclados), D (Gigantea) and E (Spaethii), with herbicide present, had reduced survival rates in comparison to Clone A (Rosewarne White) with herbicide present
- Clones C (Dasyclados), D (Gigantea) and E (Spaethii) planted at 0.5 m centres had increased chance of survival compared to Clone A (Rosewarne White) at the same planting density

Block 3

- Stools coppiced annually or once had reduced chances of survival compared with no coppicing
- The use of fertiliser reduces the chance of survival compared to not using fertiliser
- Stools planted at 0.5 m centres had reduced chance of survival compared to those planted at 1.0 m spacing

- The use of both herbicide and fertiliser increased the chance of survival compared to any other combination of these two variables
- The use of fertiliser and the practice of coppicing once (i.e. coppiced in year 2) increases the chance of survival compared to using fertiliser and not coppicing
- The use of herbicide and the practice of coppicing once increases the chance of survival compared to using herbicide and not coppicing
- The use of herbicide on stools planted at 0.5 m densities increases the chance of survival compared to any other combination of these two treatments.

Across all three blocks, the odds ratios (Figure 3.3.7 and Table 3.17) indicated that clones C (Dasyclados) and D (Gigantea) showed the highest chance of survival whilst clones A (Rosewarne White) and E (Spaethii) performed the worst. Block 3, as for year 1 results, continues to show a dramatic increase in the survival of Clone A (Rosewarne White) relative to the other clones. In all three blocks Clone B (Burjatica Germany) had lower odds ratios than clones C (Dasyclados) and D (Gigantea). Clones C (Dasyclados) and D (Gigantea) have a higher odds ratio in block 2 than block 1 and block 3 produces higher odds ratios for clones A (Rosewarne White), B (Burjatica Germany), C (Dasyclados) and D (Gigantea).

Analysis of the odds ratios (Figures 3.3.7 and Table 3.17) with the percentage survival tables (Tables 3.10 – 3.12) for each block can be used to summarise the effect of the treatments upon the survival rates over the three years. These are as follows –

- Clones C (Dasyclados) and D (Gigantea) performed well throughout the 3 blocks
- Clone E (Spaethii) consistently performs the worst
- Block 3 exhibits the strange effect of dramatically increasing the survival of Clone A (Rosewarne White)
- Apart from when herbicide was used in block 2, not coppicing the trees gave the highest proportion of trees surviving
- The use of herbicide had a strong effect on increasing the survival rates

- Fertiliser did not have an effect in block 1. In block 2 it caused an increase in the proportion surviving. In block 3 it caused a decrease in the proportion of stools surviving especially when they had not been coppiced, but increased the survival rate for those stools coppiced once or twice.
- When herbicide was used there was only a very small difference between the proportion surviving for stools planted at 0.5 m and 1.0 m centres.

Analysis of the survival results over the three years are on the whole consistent with those results for year one with block 3 continuing to produce results which are not comparable with those noted for blocks 1 and 2.

4.1.4 Statistical Interpretation of the Total Yield over the Three Years

Table 3.18, the General Linear Model of the treatment interactions indicated all the main treatment variables to be significant in their influence upon yield. Figure 3.3.11, a plot of the relative effects of all treatments, shows the results from the multiple comparisons to give an overall impression of the variability of the influence of the treatments and willow clone upon yield. Figure 3.3.12 is the final plot and illustrates the overall proportion of clones surviving against yield and against block.

From these analyses it is possible to draw a number of conclusions about the clones or treatments that result in higher yields. These can be summarised as follows –

- **Clone** - Clone D (Gigantea) produced the highest average yield and high values for the proportion surviving. Clone C (Dasyclados) produced a lower yield than D (Gigantea) but also high values for the proportion surviving and in both cases yield and survival were not significantly different from Clone D (Gigantea). Clone B (Burjatica Germany) produced lower survival and yield values than C and D and Clone E (Spaethii) performs the worst. Clone A (Rosewarne White) gave low values for the proportion surviving in blocks 1 and 2 but high values in block 3, consequently it did not produce a high value for overall yield.

- **Coppicing –** Not copping the stools gave a higher proportion surviving and a greater average yield than coppicing once or twice.
- **Herbicide –** Using herbicide had a strong effect on increasing the yield and proportion surviving.
- **Fertiliser –** The use of fertiliser was identified as having only a small effect on increasing yield and when used in conjunction with herbicide, only had an effect in block 2 by increasing the proportion surviving.
- **Spacing –** 0.5 m planting density was identified as having a small effect on increasing the yield compared to 1.0 m planting density. The uses of herbicide at both these spacings resulted in little difference in survival and hence yield between the two planting densities.
- **Block –** Block 3 was identified as producing the highest yield which also corresponded with the highest survival rates also recorded for this block. Attempting to determine why there was a strong block effect within the field trial has proven difficult. Two assumptions are proposed namely different physical limitations within the growing medium across the area of the three blocks or the nature of the weed invasion on the newly established site which commenced in block 1 and spread to blocks 2 and 3 thereafter.

4.2 Metal Concentrations in the Biomass Samples

Table 4.8 Hallside Field Trial - Metal Uptake by Individual Clones Sampled from those Plots Receiving no additional Treatments (all results expressed in mg kg$^{-1)}$

[redacted]

Metal uptake by the 5 clones used in the treatment plots was calculated and the results are presented in Table 3.19 and a condensed version in Table 4.8. Measured differences in the metal uptake between the individual clones are considered to be negligible, given the large standard deviation in the results. Comparison with other studies (Pulford and Watson, 2003; Dickinson and Pulford, 2005) does not indicate that metal uptake for these clones to be high. This however, should also be considered against the levels of heavy metals recorded in the growing medium at the site, which may be considered on the whole to be low.

4.3 Data Collected from the Additional Clones Assessed

Data gathered from the additional clones assessed as part of the Hallside Field Trial and presented in Section 3.4 clearly demonstrate the variability of results obtained from this field trial. Data were collected from clones tagged at two separate areas on the site (identified by their initial letter). Results for both areas indicate the variability of survival rates, with the V area consistently out performing the results obtained from the S area. Yield values assessed after the first year's growth only have indicated that *Gigantea, Jorunn* and *Cambell 3106* are amongst the best performing in both areas, however the yield values obtained vary.

Metal uptake by individual clones was calculated from samples taken from the biomass and, as in the treatment plots, values obtained were relatively low and variability of results high. Whilst differences in mean concentration values for metal uptake are noted, given the variability of the results obtained and the relatively low metal concentration values in the growing medium in the first instance, differences are considered as negligible. Both lead and chromium have been excluded from the results as both were deemed to be of low concentration in the initial growing medium and are not readily taken up by plant tissue.

Leaf metal concentrations, in contrast to the biomass metal concentrations were assessed from samples obtained for the months of August and September. All concentration values for the leaf material were considered to contain elevated values of metals in comparison to concentrations obtained from the biomass, particularly zinc being the more mobile element. Interestingly, the leaf metal concentration values increased from August to September, in some instances by factors of 2 to 4. Values for the leaf metal concentration were not assessed throughout the growing season so it is not possible to consider whether the uptake has risen throughout the year or whether the increase was as a result of seasonal changes in the willow causing it to relocate heavy metals from within the wood and bark to the leaves at the end of the growing season.

4.4 Conclusions

Data gathered in the field trial and discussed in this chapter have shown the variability of the results obtained from the field study. Physical and chemical constraints associated with the growing mediums found on contaminated sites, is a factor which can strongly influence the survival and growth of willow SRC on such sites in comparison to its establishment in an agricultural environment. In this study variability demonstrated itself with the different results obtained across the three experimental blocks, part of the experimental design of the field trial. The influence of herbicide in the establishment and survival of willow SRC on this disturbed and contaminated site has demonstrated positive survival benefits, whilst the addition of fertiliser has proved beneficial only when used in conjunction with fertiliser. The wholesale adoption of practices developed for growing willow SRC in agricultural soils need to be considered carefully before they are used to grow willow SRC on contaminated and disturbed land. Adaptations to these practices will be required to ensure that willow SRC can establish and survive in such harsh growing environments.

CHAPTER 5 – THE LEAF DISC SCREENING TRIAL

5.1 Introduction

The development of a rapid screening technique to assess the potential of willow SRC to withstand elevated concentrations of heavy metals in the growing medium would result in the speed of determining clone suitability to individually contaminated sites being greatly accelerated. At present determining the suitability of individual willow clones for growing in a contaminated growth medium can at best be achieved either by undertaking growth trials in either a laboratory or field environment or by assessing their establishment in soil-less conditions such as nutrient film techniques (Cooper,1979). All these techniques can be time consuming requiring the individual clones to be established, maintained and assessed continuously over a measured time period or over one or several growing seasons.

Work undertaken by the Water Research Council (1998) as part of an European Commission Study funded under the Environment and Climate Programme considered the potential of utilising leaf segments floating in nutrient solution contaminated to varying concentrations of cadmium solutions to assess the tolerance of individual willow clones to heavy metals. After a length of time the degree of leaf damage was assessed and compared against known growth trials for willow clones grown in contaminated soils. It was hoped that these initial attempts at developing an early screening technique could be developed further and used to assess the suitability of other willow clones via their tolerance of heavy metals to assist in their selection in growth trials on contaminated sites. This small study was intended to replicate the work undertaken by the Water Research Council (1998) and to consider whether there was any potential to extend the use of the leaf disc trial to identify the effect of heavy metals upon other clones of willow not already considered.

5.2 Methodology

Willow leaves collected from 18 differing clones were collected and washed to remove any dust or debris. Three leaf discs measuring approximately 10.0 mm diameter were cored from the individual leaf samples and placed to float upright in three replicate petri dishes containing either the nutrient solution of 0.1 mM $Ca(NO_3)_2 . 4H_2O$ or the respective nitrate salts for cadmium, lead, chromium, nickel, copper and zinc all at concentrations of 20 uM, of the metal in a 0.1 mM solution of $Ca(NO_3)_{2.}$ (Water Research Council, 1998)

The leaf discs placed in petri dishes containing 20 ml of solution were covered and placed in an incubator at 22 C^o. Observations were made of the individual clones after 8, 14 and 21 days. Initially it had been intended to undertake the screening trials to consider the effect of varying concentrations of the metal salt i.e. 50 uM, 20 uM, 10 uM and 5 uM. However as a pilot study had failed to show any visual difference between the differing concentrations the full trial was undertaken using the concentration of 20 uM only.

Prior to undertaking the full trial the pilot trial had employed both petri dishes initially and then Buchner flasks evacuated of air after the disks had been placed on the surface of the solution. This was considered necessary as it was felt that air trapped between the leaf underside and the metal solution might have prevented the leaf discs from absorbing the metal solution. No visible difference was recorded over measured time periods consequently the full trial was undertaken using petri dishes all at the one metal concentration only and references containing the nutrient solution only.

The clones used in this trial were as follows –

Table 5.1 Varieties of Willow Clones used in the Leaf Disc Trials

Common Name		Parentage
V1.	Q83	*S. triandra x viminalis*
V2.	Calodendron	*S. caprea x viminalis x cinerea*
V3.	Jorunn	*S.viminalis*
V4.	Cambell 3106	*S.viminalis*
V5.	Spaethii	*S. spaethii*
V6.	Niginians Prunifolia	*S. caprea x viminalis*
V7.	Candida	*S. candida*
V8.	Delamere	*S. aurita x cinerea x viminalis*
V9.	Tora	*S.viminalis x scwerinii*
V10.	Bjorn	*S. viminalis x schwerinii*
V11.	Delamere	*S. aurita x cinerea x viminalis*
V12.	Gigantea	*S.viminalis*
V13.	Stipularis	*S. stipularis*
V14.	Bjorn	*S.viminalis x schwerinii*
V15.	Orm	*S.viminalis*
V16.	Rapp	*S. viminalis*
V17.	Dasyclados	*S. dasylados*
V18.	Jor	*S. viminalis*
V19.	Coles	*S. caprea x cinerea*
V20.	Ulv	*S. viminalis*

As the leaf samples were collected late in the growing season care was taken to ensure that the leaves did not exhibit rust or insect damage. This was considered necessary to ensure that any damage caused to the leaf discs was as a result of its interaction with the metal solution and not other factors.

5.3 Results

Throughout the incubation period visual assessments were recorded of the discs at 8, 14 and 21 days. At the completion of the study, 3 representative discs from each treatment for each clone were placed next to each other and scanned to provide a visual record of the degree of leaf damage observed. These are reproduced in Figures 5.1 to 5.7.

Analysis of the degree of leaf damage or chlorosis exhibited by the leaf discs showed variation between individual clones and treatments. Some discs would show a circular damage around the leaf edge whilst others would have spots on the leaf disc away from the edge. As a general rule those leaf discs that showed any signs of damage turned yellow in the first instance before turning necrotic. Whilst many of the leaf discs used in this study showed some visual change upon being incubated in the metal solution others showed no obvious visual damage.

An assessment was made of the damage to the leaf discs in accordance with scaled criteria as follows –

Scale	Visual Assessment
1	No Visual Damage to Leaf
2	Some Visual Damage (< 25%)
3	50% Damage to Leaf Disc
4	Majority of Leaf Disc Damaged <25% Green
5	Leaf Disc Completely Damaged

Table 5.2 Visual Assessment of Leaf Damage According to Scaled Criteria

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18	V19	V20	Average	SD
Calcium Nitrate	1	1	1	1.6	4	1	3	3	5	1	4.6	1	1.6	1	1	1.6	1	1	1	4	1.97	1.4
Cadmium	5	2.3	5	5	2	2	2	3	2	2	2	3	2.6	2	1.3	2	2	2	2	3	2.61	1.1
Chromium	3	3.6	3	4	2	2	3	4.3	1	1	1	2	1	1	1	2.3	1	1	1	1	1.96	1.1
Lead	1	2	2.6	4	2	1	4.3	2.6	1.3	1	2	2	3	1	1	3	1	1	1	1	1.89	1.1
Copper	4	3.3	2.6	4	2	2	3.3	4.6	2	1	1	1	2.3	1	2	3	1	2	1	1	2.20	1.2
Nickel	2	2	2	3	1.6	2	1.6	2.6	1.3	1	1.3	2.3	1	2	2	1.3	1	2	1.3	1	1.71	0.6
Zinc	2	4.3	5	5	2	1.3	1.3	2.3	2	1	1.3	1	1.3	1	1	3	1	1	1	1	1.94	0.4
Total	18	18.4	21.2	26.6	15.6	11.3	18.5	22.4	14.6	8	13.2	12.3	12.8	9	9.3	13.2	8	10	8.3	12	14.14	5.3

5.3.1 Leaf Discs Incubated at 0.1mM Calcium Nitrate Solution for 21 Days (Figure 5.1.)

An average value of 1.94 was recorded on the visual assessment scale suggesting that most discs exhibited less than 25% leaf damage after being incubated in the calcium nitrate solution. Analysis of the leaf discs incubated in Calcium Nitrate reference solution only, showed that most of the clones exhibited little or no leaf damage with the notable exception of V5 Spaethii, V7 Candida, V8 Delamere, V9 Tora, V11 Delamere and V20 Ulv. V7 Candida showed contrasting results as some leaf discs were completely necrotic, whilst others seem unaffected.

5.3.2 Leaf Discs Incubated at 20uM Cadmium Solution for 21 Days (Figure 5.2)

All leaf discs incubated in the 20uM Cadmium solution showed some evidence of leaf damage, with V1 Q83, V3 Jorunn, V4 Campbell 3106 , V8 Delamere (but not V11 Delamere), V12 Gigantea and V20 Ulv showing damage exceeding the average value of 2.61 on the visual assessment scale.

5.3.3 Leaf Discs Incubated at 20uM Chromium Solution for 21 Days (Figure 5.3)

The average value for the damage caused by the chromium solution was 1.96 indicative of less than 25% leaf damage, however V1 Q83, V2 Calodendron, V3 Jorunn, V4 Cambell 3106, V7 Candida, V8 Delamere and V16 Rapp exhibited damage in excess of the mean value recorded. Notable exceptions to these clones were those of V9 Tora, V10 Bjorn, V11 Delamere, V13 Stipularis, V14 Bjorn, V15 Orm, V17 Dasyclados, V18 Jor, V19 Coles and V20 Ulv which seemed unaffected in the metal solution.

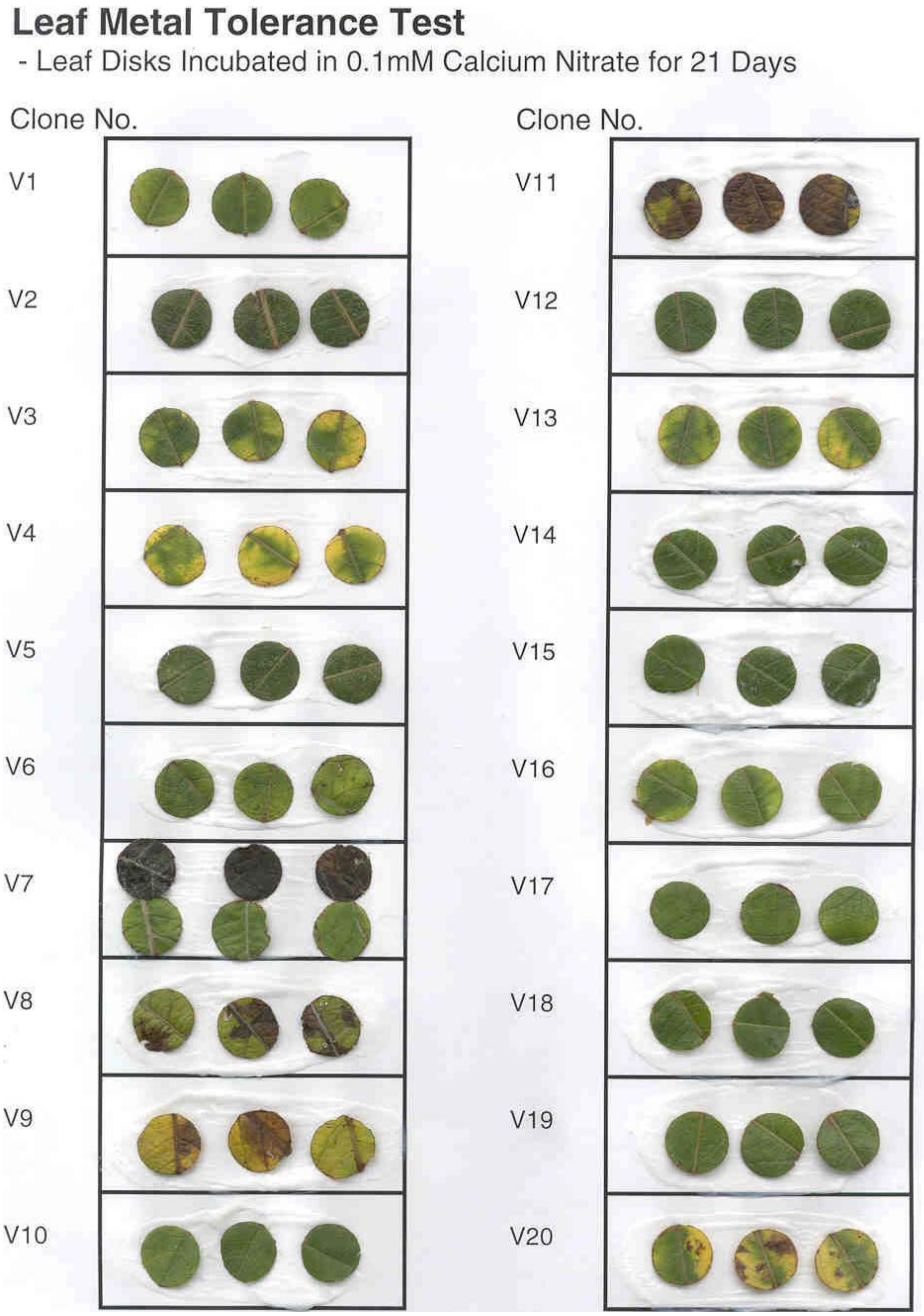


Figure 5.1 Leaf Discs Incubated at 0.1mM Calcium Nitrate Solution for 21 Days

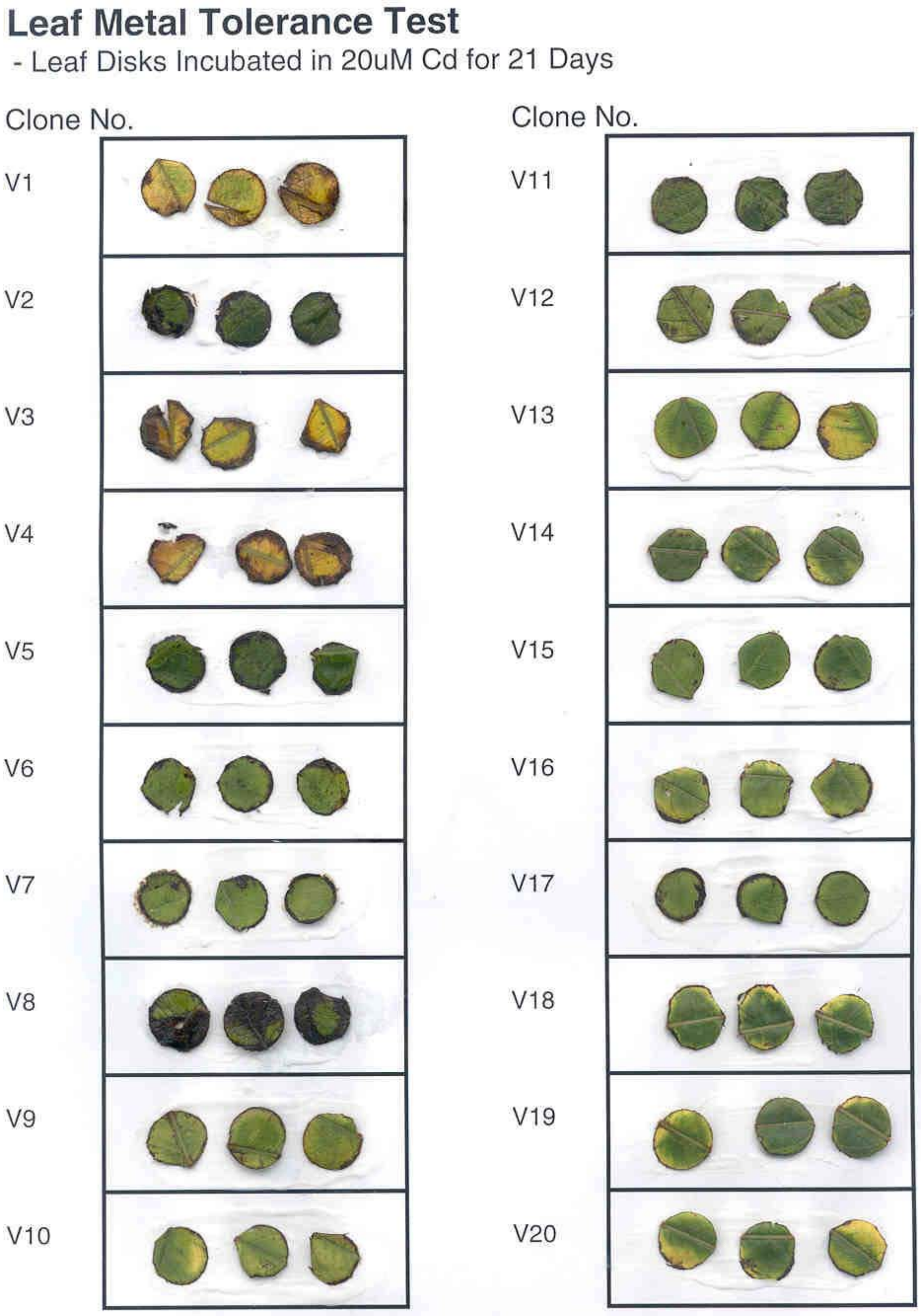


Figure 5.2 Leaf Discs Incubated at 20uM Cadmium Solution for 21 Days

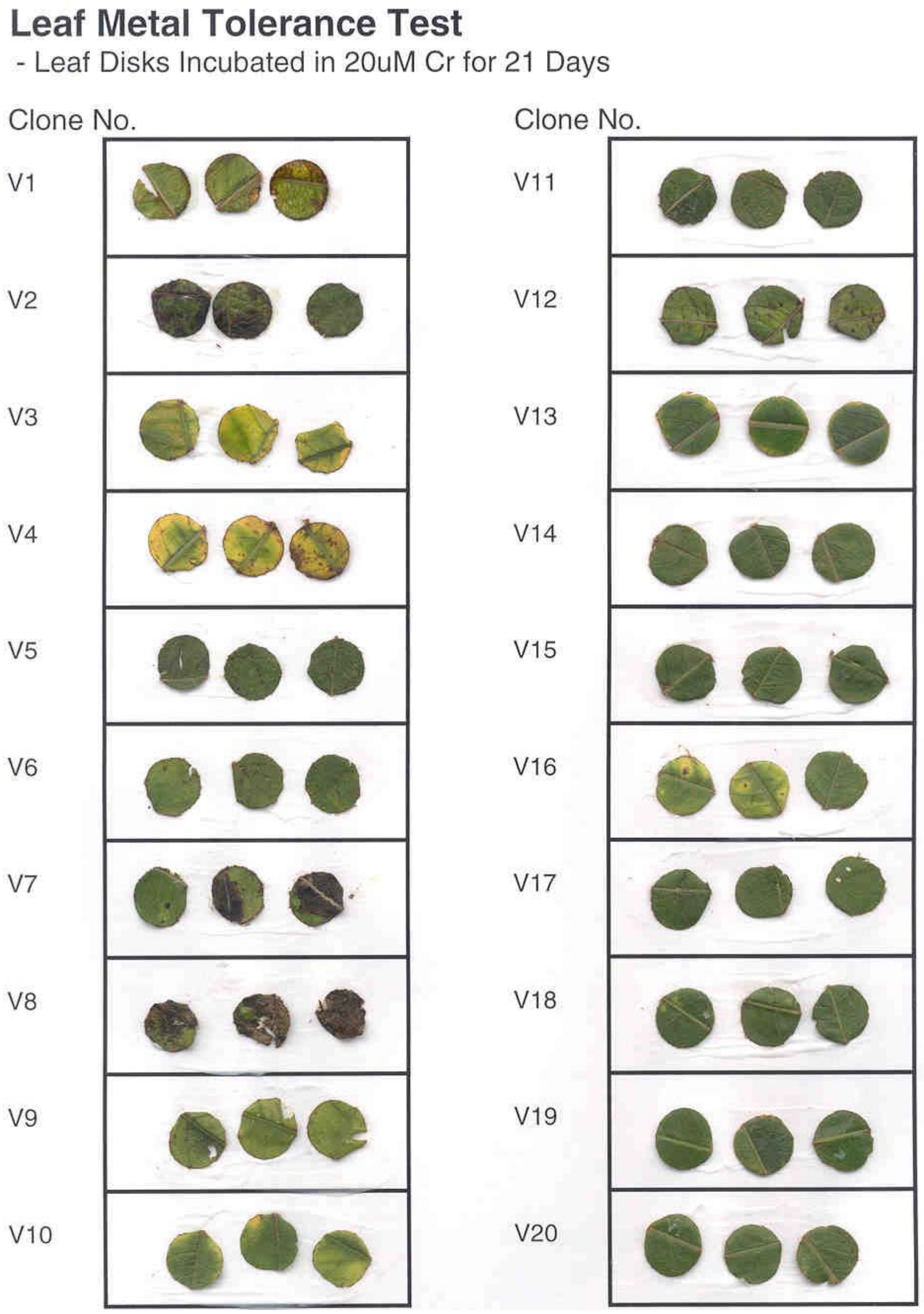


Figure 5.3 Leaf Discs Incubated at 20uM Chromium Solution for 21 Days

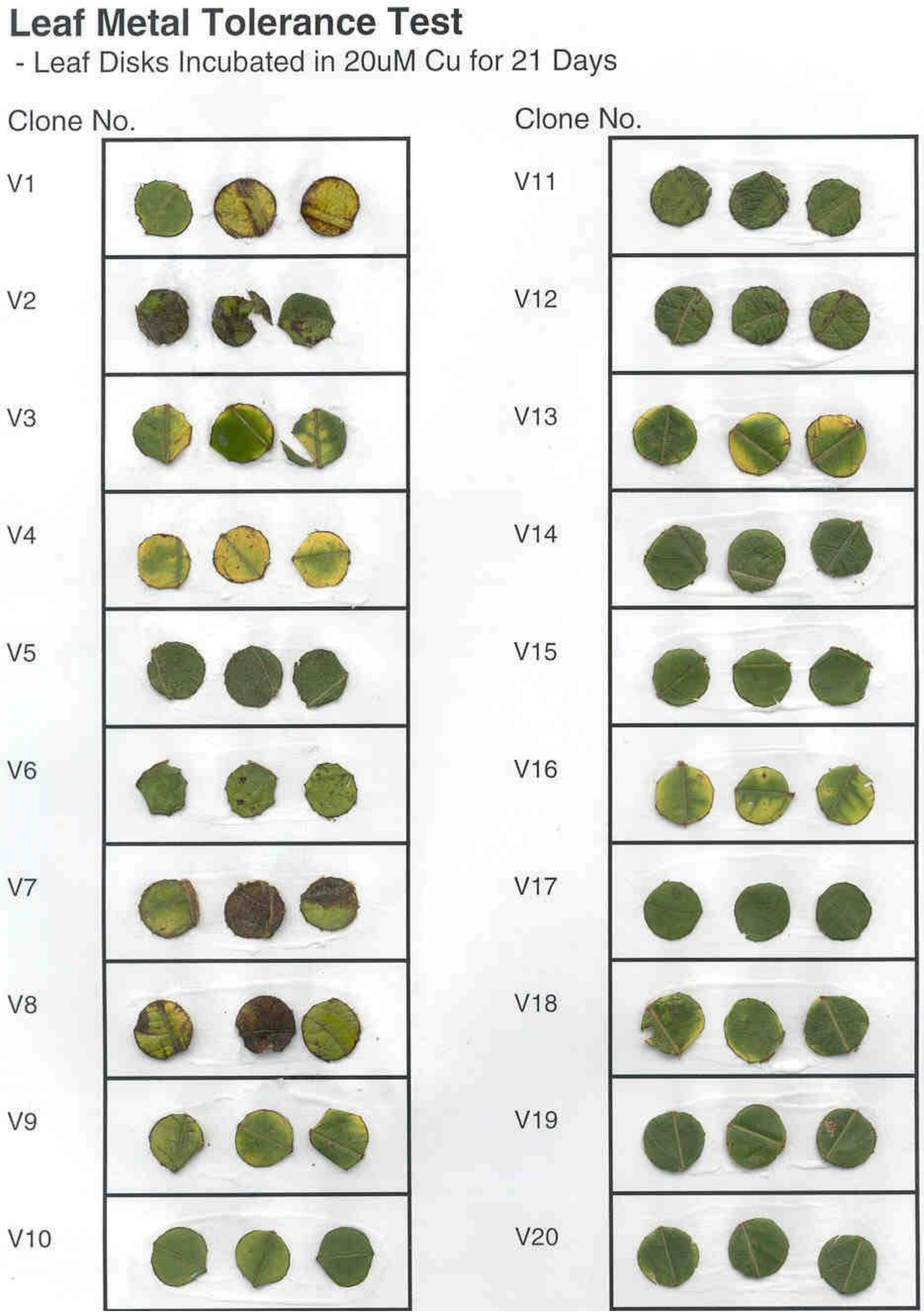


Figure 5.4 Leaf Discs Incubated at 20uM Copper Solution for 21 Days

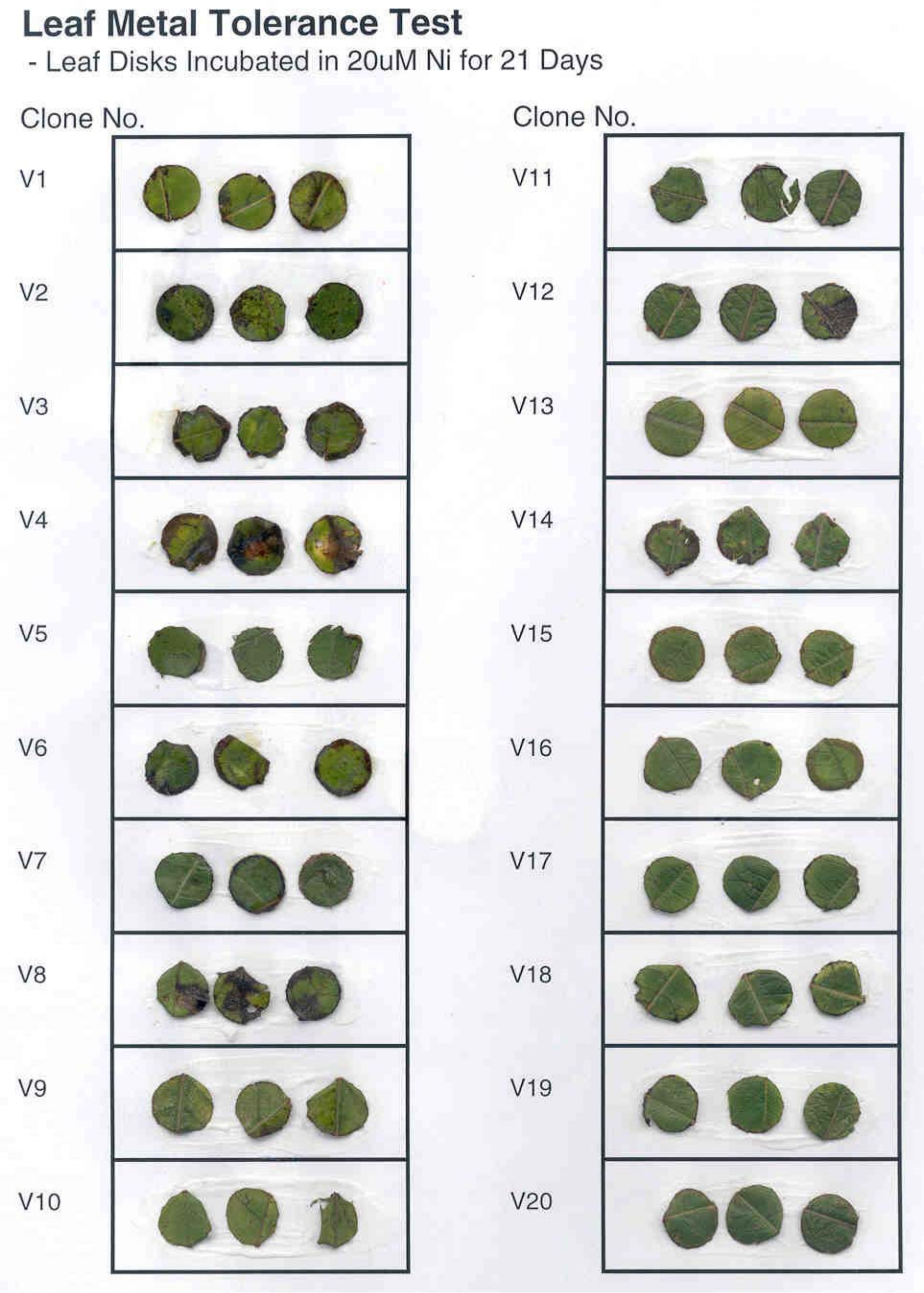


Figure 5.5 Leaf Discs Incubated at 20uM Nickel Solution for 21 Days

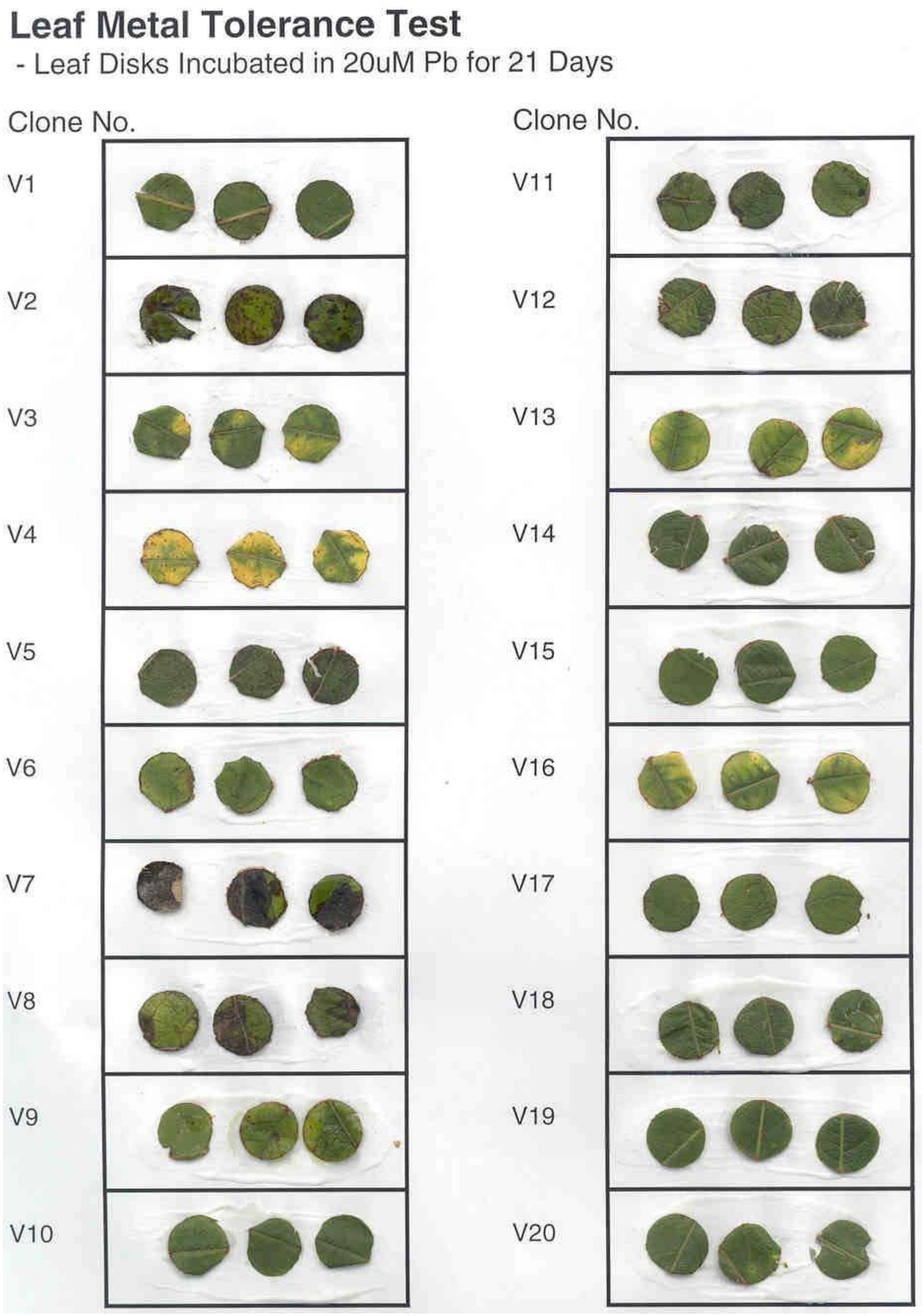


Figure 5.6 Leaf Discs Incubated at 20uM Lead Solution for 21 Days

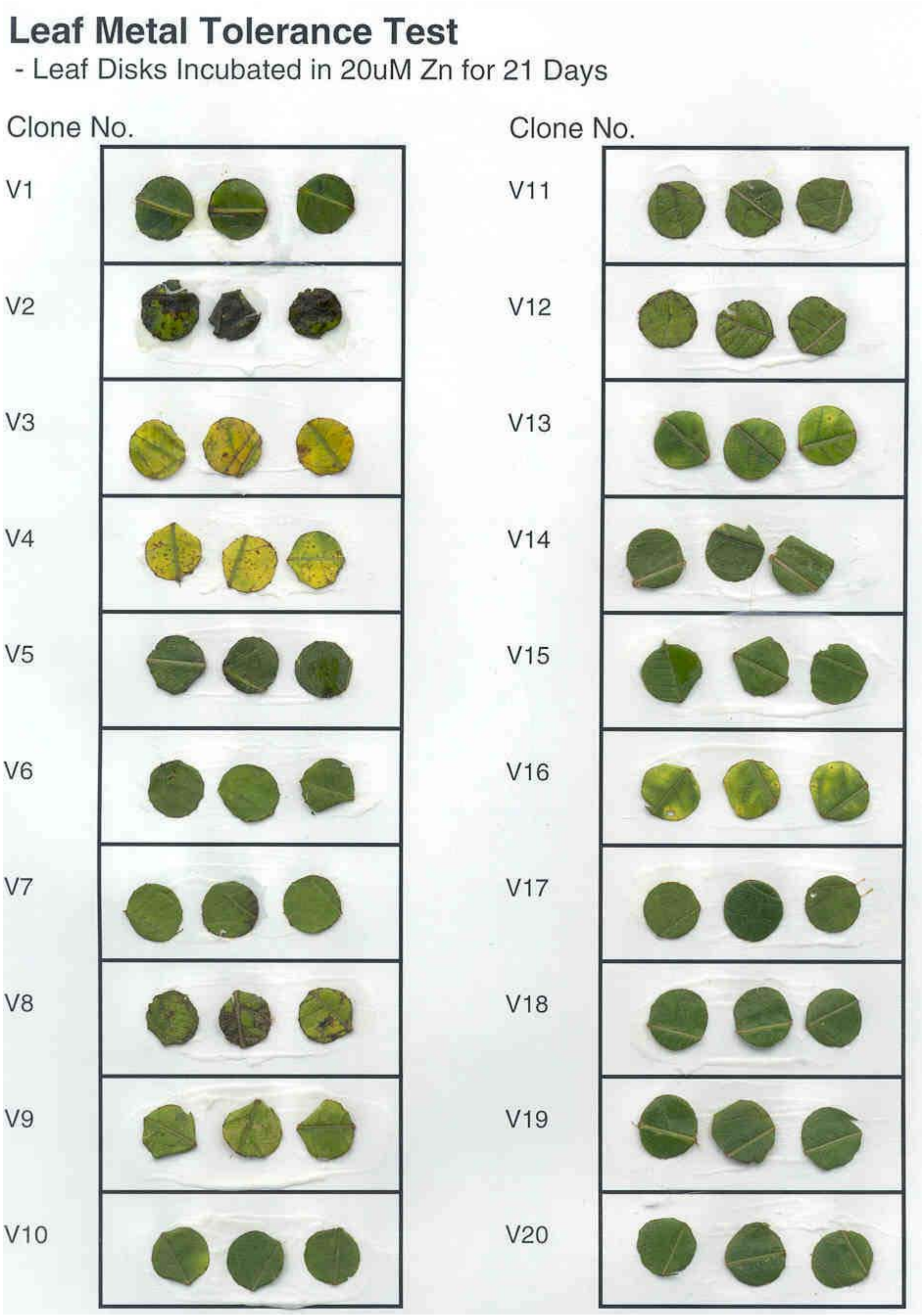


Figure 5.7 Leaf Discs Incubated at 20uM Zinc Solution for 21 Days

5.3.4 Leaf Discs Incubated at 20uM Copper Solution for 21 Days (Figure 5.4)

Recorded leaf damage was noted as being more pronounced for V1 Q83, V2 Calodendron, V4 Campbell 3106, V7 Candida, V8 Delamere and V16 Rapp exceeding the mean value of 2.2, which is greater than 25% leaf damage. Minimal damage was recorded in those leaf cells obtained from V5 Spaethii, V6 Niginians Prunifolia, V9 Tora, V10 Bjorn, V11 Delamere, V12 Gigantea, V14 Bjorn, V15 Orm, V17 Dasyclados, V18 Jor , V19 Coles and V20 Ulv. All other leaf cells had some indication of leaf damage although not as pronounced as those indicated previously.

5.3.5 Leaf Discs Incubated at 20uM Nickel Solution for 21 Days (Figure 5.5)

A notable difference observed from the leaf discs incubated in the nickel solutions was the differing coloration of the damage caused. Whilst the leaf disc damage noted for the other treatments gave a range of leaf degradation from green to yellow to black, the notable discoloration of the leaf disc after 21 days is to black. No leaf discs were considered as having been unaffected by the metal solution, however the degree of leaf damage exceeded the average value of 1.71 in those clones numbered V1 Q83, V2 Calodendron, V3 Jorunn, V4 Cambell 3106, V6 Niginians Prunifolia, V8 Delamere, V12 Gigantea, V14 Bjorn, V15 Orm and V18 Jor.

5.3.6 Leaf Discs Incubated at 20uM Lead Solution for 21 Days (Figure 5.6)

The clones which were assessed as having the greatest leaf disc damage included V3 Jorunn, V4 Cambell 3106, V7 Candida, V8 Delamere , V13 Stipularis and V16 Rapp. Below average damage was recorded for V1 Q83, V6 Niginians Prunifolia, V9 Tora, V10 Bjorn, V14 Bjorn, V15 Orm, V17 Dasyclados, V18 Jor, V19 Coles and V20 Ulv.

5.3.7 Leaf Discs Incubated at 20uM Zinc Solution for 21 Days (Figure 5.7)

Leaf damage greater than the mean value for all discs was observed for V2 Calodendron, V3 Jorunn, V4 Cambell 3106, V8 Delamere and V16 Rapp. Most of the other leaf discs exhibited some damage with the V10 Bjorn, V12 Gigantea, V14 Bjorn, V15 Orm, V17 Dasyclados, V18 Jor, V19 Coles and V20 Ulv showing the least recorded measurable damage to the leaf discs.

5.4 Discussion

The results obtained from this screening trial would suggest that the leaf damage suffered by leaf discs obtained from differing clones of willow to be consistently more pronounced amongst individual cultivars numbered V1 Q83, V2 Calodendron, V3 Jorunn, V4 Cambell 3106, V5 Spaethii, V7 Candida, V8 Delamere and V9 Tora . Comparisons of the results for V8 Delamere with V11 Delamere do not match, however the measured assessment totals for V10 Bjorn and V14 Bjorn are on the whole comparable.

Limitations are imposed upon this quick screening test by the lack of available information to allow comparison of these screening trials with information for willows established in growing mediums of a similar metal contamination. Work undertaken by Pulford et al (2003) would seem to indicate that Calodendron, Delamere and Candida are able to tolerate relatively high levels of Nickel, Zinc, Copper and Cadmium and produce satisfactory growth. The ability of Jorunn to uptake heavy metals in the research undertaken by Pulford et al. (2003) showed that its metal uptake was less and growth visually assessed as being poorer than that of the other three willow clones. If this is the case then we are presented with two scenarios where willow clones are able to grow quite happily in metal contaminated mediums taking up heavy metals i.e. they are unaffected by the metals accumulated in the plant tissue. Alternatively the cultivars indicate a high concentration of metal uptake in the plant tissue but they do not produce satisfactory growth i.e. the biomass produced is low.

If the intended use of the screening trial is to identify those clones that are able to either tolerate or alternatively absorb heavy metals and produce large volumes of biomass then clearly problems could be encountered for those clones identified in screening trials that are tolerant of heavy metals but do not produce particularly large volumes of biomass.

How this could be addressed via a screening trial is uncertain. Identifying clones with heavy metal tolerance in itself is not the goal.

Willow clones able to produce large volumes of biomass and take up relatively high levels of heavy metals can provide opportunities for site decontamination and a source of revenue through the sale of biomass. This is the scenario that should be aimed for with any screening trial or at least a scenario where willow clones are able to tolerate the growing conditions, produce large volumes but do not take up heavy metals into their plant structure, at least their biomass yield would be a quantifiable and beneficial output from such a development.

The intention of this adjunct to the core of this thesis was to replicate work already undertaken by the Water Research Council (1998) and to consider whether their initial work could be expanded to other clones and metals. Limitations in the availability of comparative data for willow grown in contaminated mediums limit the scope of the research at present. Further comparative field trials of individual willow cultivars grown in heavy metal contaminated growth mediums are considered to be necessary before any meaningful interpretation can be provided of the leaf disc screening technique.

CHAPTER 6 – AN EVALUATION OF THE BENEFITS OF UTILISING DISTURBED AND CONTAMINATED SITES FOR THE PRODUCTION OF WILLOW SRC

6.1 Introduction

From the outset of this study the commercial growth of willow SRC on disturbed and contaminated land is not an operation that is considered to be viable in its own right. Constraints both physical and chemical imposed on the ability of the willow to establish and grow were considered to limit its potential yield particularly when compared to yields from its growth in better quality arable sites.

Experience with its growth on arable land in the UK has to date not seen large scale adoption on agricultural land, even with the funding that is possible through such sources as the Woodland Grant Scheme and Arable Area Aid Scheme and its continued coverage and promotion in the Farming Press (Driver, 2004). Projects involving the growth of willow SRC that have been initiated have been very focussed in their goal, usually involving the supply of a known end-user.

This thesis from the outset did not intend that the production of willow SRC on disturbed and contaminated land would compete on a level playing field with willow from agricultural land. The objective of this research was to attempt to demonstrate the potential yields possible from growing willow SRC on a capped steelworks site and to consider the implications of various silvicultural practices which could be used to optimise the growth of willow in such harsh growing mediums.

The sale of willow biomass as a commodity where a potential end-user has been identified has been known to attract sale values of £44 per delivered dry tonne (Alston, 2004). Utilising disturbed and contaminated sites for willow production is considered as a positive use of many of these sites given their number and areas involved throughout the UK, however the returns derived from the sale of willow biomass will not be sufficient to cover the overall establishment costs. It is argued that to determine the true benefit of growing willow SRC on contaminated and disturbed industrial sites the value of both environmental and social factors must be considered also.

6.2 The Potential Benefits of Trees and Woodlands

The potential benefit of restoring derelict land to woodland is well known (DOE, 1996) and the possibility of utilising such sites has already been documented (Dobson and Moffat, 1993, Moffat and McNeill, 1999, Dobson and Moffat, 1999, Dickinson, 2000). Table 6.1 reproduced below was used by the Department of Environment to emphasise the potential benefits of urban greening. Whilst the report seeks to promote the benefits that can be derived from enhancing the value of existing green spaces it also promotes and provides case studies of the benefits of greening areas of derelict land.

One project worthy of note in this report is the NUVIL (New Uses for Vacant Industrial Land) in Knowsley, Liverpool undertaken by the St Helens, Knowsley and Sefton Groundwork Trust in partnership with the local business community, Knowsley Borough Council and the Mersey Forest Trust (DOE, 1996). The de-industrialisation of the area in the mid 1980’s had produced a large number of derelict sites in the area that were proving expensive to maintain and were unlikely to be successful in attracting alternative business uses. The project in itself had the objectives of –

- Returning vacant land to productive use;
- Improving the condition of the land and the image of the industrial sector;
- Creating employment opportunities in woodland creation and management and the timber industry;
- Increasing the total amount of woodland in the borough;
- Measuring and researching the impact of the project.

Table 6.1 The Potential Benefits of Urban Greening (DOE, 1996)

Economic Regeneration

- Improved image helps inward investment and business retention;
- Positive publicity for business
- Direct employment opportunities;
- Attracting tourism;
- Contributes to sustainable development.

Environmental

- Supporting plant and animal communities;
- Pollution control;
- Influencing micro-climates;
- Support biodiversity;
- Recharging ground water levels;
- Reduce problems of soil erosion;
- Better urban greenspaces reduces journeys to and pressure on the countryside.

Educational, Social and Cultural

- Improved leisure and sports facilities;
- Better understanding of nature and the environment;
- Enhanced well-being through contact with nature;
- Healthier life-styles;
- Improved self-image, self-esteem and confidence for communities;
- Stronger, better integrated communities

Willow biomass, coppice woodland and long term woodland were all key components of the project. Funding for the project was secured through grant aid, earned income and the sale of biomass and up to 1995 had contributed towards the –

- Treatment of 74 hectares of land;
- Planting of more than 270,000 trees;
- Planting of 42 hectares of long term woodland;
- Planting of 13 hectares of coppice;
- Planting of 14 hectares of biomass;

- Planting of 5 hectares of wildflowers;
- Promotion of the use of biomass and the approach of the project through conferences;
- Clearing of three sites in readiness for industrial development;
- Creation of 2.5 permanent jobs;
- Local borough council's targets for the Mersey Forest Campaign.

This project represents just one example of the benefits of greening an environment. Further studies published by the Department of the Environment in 1996 (DOE, 1996) considered the benefits of urban woodland for local air quality. The report was intended to evaluate possible tree species, woodland types and planting configurations that could be employed to maximise the removal of harmful pollutants and in so doing improve public health.

The value and importance of trees in the rural and urban environment are well documented for sporting, conservation and recreation purposes. Guidance for the management of such areas issued by the Forestry Commission have long since recognised this (Forestry Commission, 1984), and indeed within the evolution of British forestry policy over the last 100 years, the role and importance of forestry within British society has evolved to reflect the change in values associated with British Forestry. This is illustrated in table 6.2, which reflects the changes in forestry policy in the UK over approximately 100 years. Initial forestry policy was to focus upon the need to supply timber. Today forestry policy in the UK must also consider the wide benefits that forests can bring to communities and the environment.

Table 6.2 Evolution of British Forestry Policy 1919 – 1987 (Tsouvalis – Gerber, 1998)

Year	**Basis**	**Implication**
1919	Forestry Act	Forestry Commission (FC) set up: Aim: To build a strategic reserve of timber
1927	Forestry Act	FC enabled to make bylaws (e.g. concerning access to land, etc)
1945	Forestry Act	FC to rebuild timber reserve, applying systematic techniques
1946	Forestry Act	FC to administer a Dedication Scheme to boost private forestry
1951	Forestry Act	No trees to be felled without a licence from the FC –continues system introduced in the Second World War
1957	Zuckerman Review	FC obliged to balance employment in remote rural regions
1967	Forestry Act	Consolidates previous Acts
1968	Country Acts	FC to have regard for conservation, natural beauty and amenity: recreation
1972	Unfavourable cost-benefit study of the Treasury	FC to maintain employment and enhance the environment. Grant Aid Schemes closed
1980	Policy Statement	FC to continue and expand afforestation especially private afforestation
1981	FC disposal of land begins	
1981	Wildlife and Countryside Act	FC to balance forestry and environment interests
1985	Broadleaves Policy	FC to encourage broadleaved planting; special provisions made for ancient woodlands
1987	Countryside Commission Forest Policy	FC to create Community Forests /Multi-purpose Forests

6.3 Quantifying the Benefits of Woodlands/ Forests

Quantifiable benefits of woodlands, forests and willow short rotation coppice production could simply be measured in terms of the saleable timber or biomass production alone and the commercial opportunities that this raw material presents, however this represents one benefit only. The difficulties in arriving at robust costs for establishing Willow SRC in the UK have already been noted (B9 Energy Biomass Ltd, 2002). Arriving at a monetary value for the full benefits of a site growing willow SRC is even more complex due to the requirement to place a value on environmental and social benefits that are unquantified and non-marketable with no direct monetary value (Glasgow City Council, 2004).

Research undertaken in Sweden (Borjesson, 1999) has attempted to quantify the benefits of cultivating energy crops. The benefits of growing perennial energy crops have been estimated to give an economic value for the environmental benefits that can be attributed to their cultivation at both a global and site-specific level. Factors considered to be site specific in their benefit have included the reduction in costs to farmers for their production with environmental improvements being considered as a benefit to society as a whole.

Calculations on the benefits of cultivating energy crops (Borjesson, 1999) have been based upon differing concepts in attaining the costs of an activity or practice. In the work of Borjesson (1999) calculation of the damage caused by an activity has utilised the restoration, avoidance, or the substitution cost methods to provide an indication of the value of this activity. The damage cost is intended to quantify the cost of environmental damage caused by a human activity, the restoration cost refers to the cost of repairing and restoring environmental damage, whilst the avoidance cost simply refers to the cost of avoiding environmental damage in the first instance. Substitution costs have been referred to as the costs of achieving a similar environmental effect to that from the ecosystem being studied, but in another way.

Costs calculated by Borjesson (1999) have included those being considered as direct costs such as reductions in costs to the energy crop farmer and external costs such as environmental improvements that benefit society as a whole. Utilising the valuation method adopted above has enabled Borjesson (1999) to provide an economic valuation of various environmental effects such as –

- Greenhouse gases
- Nutrient leaching
- Heavy metals
- Soil fertility and erosion
- Municipal waste treatment (Sewage sludge)
- Biodiversity
- Recreation

The maximum annual economic value of the changes in environmental impact when perennial energy crops are used to replace food crops in Sweden are illustrated in Table 6.3. When social and environmental benefits are attributed to the cultivation of energy crops Borjesson (1999) has attempted to demonstrate that an economic assessment can be made of these, however he urges that caution be exercised in the calculations, as they will vary dependant on the initial assumptions made, with the choice of valuation method also influencing the values obtained. The economic values derived in this research for social and environmental benefits were based upon a Swedish scenario, which would require adaptation for other countries.

Table 6.3 The maximum annual economic value of the changes in environmental impact when perennial crops are used to replace annual food crops in Sweden, and the maximum area, when cultivations that generate the highest value are given priority* (Borjesson, 1999)

Environmental changes That can be achieved on the same cultivation site	Area of energy crop cultivation (1000 ha)	Σ Area of energy crop cultivation (1000 ha)	Amount of biomass (PJ)	Σ Amount of biomass (PJ)	Economic value (US $/GJ)	Economic value Total Million (US$)	Economic value Σ Total Million (US$)
Mineral soils							
1.Waste water treatment Accumulation of soil C Increased soil fertility	100	100	24	24	5.1	120	120
2. Reduced N leaching: buffer strips Reduced P leaching: buffer strips Accumulation of soil C Cadmium removal Increased soil fertility	71	171	13	37	3.5	4.5	165
3. Landfill leachate treatment Accumulation of soil C	1	172	0.2	38	3.2	0.7	166
4.Reduced wind erosion Accumulation of soil C Reduced N leaching: in general Cadmium removal Increased soil fertility Reduced N_20 emission	28	185	2.5	40	1.9	4.8	171
5.Reduced water erosion Accumulation of soil C Reduced N leaching: in general Cadmium removal Increased soil fertility Reduced N_20 emission	28	213	5.0	45	1.6	8.3	179

6. Recirc. Of sewage sludge Accumulation of soil C Increased soil fertility	134	347	24	69	1.6	39	218
7.Reduced P leaching: buffer strips Accumulation of soil C Cadmium removal Increased soil fertility	48	395	8.6	78	1.3	12	230
8.Reduced N leaching: in general Cadmium removal Increased soil fertility Reduced N_20 emission Organic soils	1100	1495	200	278	1.0	200	430
9. Reduced CO_2 emission Reduced N leaching: in general Cadmium removal	138	1633	20	298	0.61	12	442

* The maximum area of energy crop cultivation that generates the different environmental changes is based on Borjesson (1999). The economic value of increased accumulation of soil carbon in mineral soils and reduced N2O emission from mineral soils is based on a substitution cost equivalent to US$ 0.5/GJ (US$ 180/ tonne C).

Willis et al. (2003) in a report to the Forestry Commission sought to include social and environmental benefits with market benefits to demonstrate the total economic value of forestry. The approach undertaken in this research identified social and environmental benefits as a major component of multi-purpose forestry. Their inclusion in an analysis of the total economic value of forestry was considered consistent with the economic, social and environmental aims of sustainable forestry and an important step in demonstrating an evidence based approach to policy. Utilising existing and new data the study aimed to provide empirical estimates of each social and environmental benefit in terms of –

- Their marginal values as an input into forest management
- Their total value across forest and woodland sites in Great Britain, and their contribution to the British economy.

The key social and environmental benefits considered in this study included recreational values, landscape values, biodiversity values, carbon sequestration, pollution absorption, archaeological benefits and the impact of forests and woodlands on water supply.

Willis et al. (2003) estimated values for the marginal benefits of woodland to be:

- £1.66 to 2.75 for each recreational visit;
- £269 per annum per household, for those households on the urban fringe with a woodland landscape view;
- 35p per household per year for enhanced biodiversity in each 12,000 ha of commercial sitka spruce forest; 84p per household per year for a 12,000 ha increase in Lowland New Broadleaved Native Forest, and £1.13 per household per year for a similar increase in Ancient Semi Natural Woodland;
- £6.67 per tonne of carbon sequestrated;
- £124,998 for each death avoided by 1 year due to PM_{10} and SO_2 absorbed by trees, and £602 for an 11 day hospital stay avoided due to respiratory illness;
- A cost of 13p to £1.24 per m^3 where water is lost to abstraction for potable uses, although for most areas the marginal cost is zero.

These values however are however intended as indicative values only. The aggregate total annual and capitalised values are reproduced in Table 6.4. The aggregated values provided are dependent upon accurate estimates of the population relevant to each factor e.g. the air pollution absorption of a woodland or forest is considered to be relatively insignificant due to the absence of large populations in close proximity to areas of woodlands. The author of this report notes the need for more accurate information on the population of relevance to different categories of social and environmental benefits, as a consequence there is generally more uncertainty about the aggregate value of woodland than the marginal values of individual social and environmental benefits.

Table 6.4 Annual and Capitalised Social and Environmental Benefits of Forests In Great Britain (£millions, 2002 prices) (Willis et al., 2003)

Environmental Benefit	**Annual Value**	**Capitalised Value**
Recreation	392.65	11,218
Landscape	150.22	4,292
Biodiversity	386.00	11,029
Carbon Sequestration	93.66*	2,676
Air Pollution Absorption	0.39*	11
Total	**1,022.92**	**29,226**

* An approximation, since carbon sequestration, and probability of death and illness due to air pollution, varies over time. More carbon is sequestered in early rotations than in later rotations, resulting in an annuity stream that is inconsistent over multiple rotations. Similarly for air pollution, that results in an individual's life being shortened by a few days or weeks at the end of the individual's life at some point in the future.

6.4 Quantifying the Benefits of Willow SRC Production on Disturbed and Contaminated Sites

A narrative of the non-marketable benefits of willow SRC Production on disturbed and contaminated sites were provided in chapter 1, with earlier sections of this chapter providing some monetary values that have been calculated for the social and economic benefits from woodland and forest areas. For the basis of comparison many of the non-marketable benefits of woodland may be considered to be similar for willow SRC grown on disturbed and contaminated sites. Given the proximity of many of these sites to urban centres and large populations the monetary values for their benefits are assumed to be high at the higher end of the scale.

Indicative values for the woodlands associated with Glasgow City Council (2004) have utilised figures derived by Willis et al. (2003) to quantify the value of 1,633 hectares of woodland within the local authority area. Open market values for the land alone have suggested values of £25 million with the addition of social and environmental values adding an additional £3.7million (however this is conceded as being an underestimation since individual trees and woodlands can have very high values depending on location and circumstances).

An interesting analysis of the value of woodlands to the housing sector in Glasgow notes that an attractive environment can add a modest 5% to house prices. With 275,000 houses in Glasgow and woodlands covering 9.25% of its area, it is assumed that 9.25% of housing would benefit from the presence of trees. This amounts to some 25,400 houses. If each unit were to have an average value of £100,000 and 5% of the £100,000 is attributed to trees, the value of the woodlands may be approximately £127 million (£77,800 per hectare).

Attempting to assess the cumulative value of producing willow SRC on disturbed and contaminated sites would be a thesis in itself. The value of the land in itself on many such sites may in many instances be negative due to the level of repair and decontamination that is required, consequently land values similar to those suggested to Glasgow City Council are not possible, however with repair and being brought back into beneficial use may attain some value in the near future.

Studies to identify the non-marketable benefits for woodlands and research undertaken in Sweden provide an useful reference point for comparison. Many of the monetary values provided in studies to date are indicative values only of social and environmental benefits, however for the purpose of this research they demonstrate that social and environmental factors are important when considering the true benefit of utilising disturbed and contaminated land for willow SRC production.

CHAPTER 7 - CONCLUSIONS

This thesis has considered the potential of utilising disturbed and contaminated land for the production of willow SRC. Such sites due to their very nature are considered to exhibit constraints both physical and chemical that can impede the effective establishment and growth of willow, however it is recommended that utilising willow SRC as a mechanism to bring contaminated and disturbed land back into meaningful production can provide many benefits in addition to the production of a biomass crop.

The prevalence of derelict and contaminated land has been noted in previous chapters, in addition to the policies of the UK government to put in place a framework to identify these areas within each local authority's area and prioritise their rehabilitation. Given the estimated areas of derelict and contaminated land within the UK the ability to remediate these sites using engineered solutions may not always be feasible. Willow SRC is considered to be a realistic solution that should be adopted by policy makers when considering rehabilitation proposals for such sites.

This thesis from the outset did not intend that the production of willow SRC on disturbed and contaminated land would compete on a level playing field with willow grown on agricultural land. The objective of this research was to attempt to demonstrate the survival rates and potential yields possible from growing willow SRC on a capped steelworks site. In addition, the implications of known silvicultural practices that could be used to optimise the survival and growth of willow in such harsh growing mediums were considered, and potential suggestions for revising established practices were explored, that would benefit willow establishment and growth in such hostile growing conditions.

End use opportunities for willow biomass in the UK are constrained despite the good intentions of government. The absence of a demand for the product does little to encourage investment in the planting of willow SRC. The need to develop sustainable outlets that can utilise the output of a site planted with willow is an area that must be addressed. Until markets evolve to use willow SRC, a project growing willow will also need to take the lead in developing an end use for the willow grown. In the context of this study the production of willow biomass and its sale is one of many benefits that is considered when assessing the feasibility of such a project.

Returns derived from the sale of willow biomass will not be sufficient to cover the overall establishment costs associated with willow SRC. To determine the true benefit of growing willow SRC on contaminated and disturbed industrial sites the value of both environmental and social factors must be considered, especially identifying those hard to quantify non-marketable benefits.

Utilising disturbed and contaminated sites for the growth of willow SRC forestry has clear potential. Data collected during the course of this research has demonstrated that there is considerable variation between the results, potentially an indication of the heterogeneity of the site being used in the trial and potentially a feature of many if not most disturbed and contaminated sites.

Results obtained from the field trial to consider the impact of various silvicultural practices upon five clones, has indicated that results from such a field study are variable. In an ideal scenario, it would be the goal of a study such as this to propose a series of clones and silvicultural practices that could be used on such sites. However, the results obtained on this site have shown that this may not be feasible. Individual clones did survive well on this site, and it could be argued that such sites should be planted using these clones, however variability of survival rates with the same clone on the same site was also a recorded outcome. In practice, willow plantations must be planted with a large variety of clones to minimise the problems of rust and disease. Excluding some of the poorer surviving clones may be an option but ensuring a large number of different clones are planted at any one site should always be practiced.

The variability in results of both the clone survival rates and yields as a consequence of the silvicultural practices used here makes suggestion of appropriate practices to be employed on disturbed and contaminated sites difficult. The block effect in the field trial showed the variability of results possible, and this was apparent in a field trail limited to a small area of the total site. Whilst this study had proposed to make suggestions as to what silvicultural practices should be employed to maximise gains on such sites, at best only general recommendations are possible based upon the results obtained. Practitioners in the area of willow production are recommended to take into account the conditions on the site that is being proposed for planting. This it is proposed should take the form of an initial small field trial or alternatively a pot experiment, if this can accurately reflect the conditions on the site proposed for planting.

The importance of implementing an effective weed management programme on a site on both the survival rates and on annual yields was the single silvicultural practice to stand out as having a positive contribution to the willow, however even this was not without its problems.

The need to explore alternative weed control methods should be considered on sites such as these to minimise costs. Chemical weed control for the successful establishment and growth of willow is well documented in agricultural soils, however chemical weed control on the disturbed and contaminated site used for this field trial has been viewed as troublesome due to the changing and evolving nature of weed populations. It may be possible to exclude herbicide use altogether with the use of clones that out compete weed growth or by under planting of willow SRC with low height grass species. The economics of growing willow SRC on disturbed and contaminated sites will always differ from agricultural sites, consequently opportunities to explore low cost weed control practices should be provided and encouraged.

The assessment of the additional clones has shown that certain clones may be more suited to the growing medium used in this field trial than others, having demonstrated a greater resilience to the site conditions of the trial. Until additional sites with differing impediments to willow growth can be assessed, it is recommended that small scale growth trials are undertaken for each derelict and contaminated site being considered for growing willow to ensure that the final clone selection employed on the entire site are capable of establishment and growth. Given the variety of willow cultivars available in the UK market, suitable cultivars for use on disturbed and contaminated sites should exist. Regrettably, advisory guidelines on the suitability of each individual cultivar to conditions found in contaminated and disturbed sites were not available at the time of the field trial, only publications relating to a few individual clones.

Yields obtained from the field trial do not compare with results obtained from clones grown in arable conditions (Macpherson, 1995), consequently any cost benefit analysis is unlikely to be positive without the inclusion of additional benefits that may be derived from its growth. Factors that must be considered for inclusion in a benefit analysis in addition to the sale of the plant tissue should include the value obtained from -

- Site enhancement to an area that would otherwise be considered as a barrier to inward economic investment;
- Ecological benefit derived from the greening of a site;
- Long term site decontamination through metal uptake;
- Utilising the site as a carbon sink towards meeting targets for reducing the emission of greenhouse gases;
- The provision of an outlet to recycle organic matter;
- The value of the willow plantation for recreation and public amenity.

Studies undertaken in the UK and in Sweden have attempted to measure these benefits to both the environment and society as a whole (Clegg, 2004; DOE, 1996; Glasgow City Council, 2004; Willis et al., 2003; Borjesson, 1999). Some of the figures that have been presented when taken into account make the benefits of growing willow SRC on contaminated and derelict sites appear attractive. Willow SRC demonstrates itself to be a versatile product with many varied uses and benefits for its growth on disturbed and contaminated sites. Economic conditions for the growth of willow SRC on such sites will differ to those grown on arable land, as such any inputs such as herbicide, which has clearly been demonstrated to be beneficial to its growth must be weighed against the cost.

The establishment of willow SRC on disturbed and contaminated sites represents an opportunity to utilise an area of land that might otherwise remain unused for generations. The benefits willow SRC can provide are varied. These can include the long term decontamination of a site or in the short term their use may be more suited to the ‘polishing’ of sites that only just exceed trigger guideline values for contamination (Ernst, 1996), the site of the field trial would be a good example of this.

Derelict and contaminated lands with immediate commercial opportunities such as house building or industrial uses are unlikely to present opportunities for willow SRC forestry. The scale of the problem in the UK alone will insure that the supply of such land will continue to outstrip demand and necessitate the need for continued innovative solutions to be proposed for their restoration. The option to utilise these sites for the production of willow SRC forestry clearly warrants consideration and in the appropriate situation should be adopted.

Given the challenging nature of contaminated and derelict sites this study would suggest that with the appropriate management, beneficial survival rates for willow SRC can be achieved on these sites. Despite all the variable results that were obtained in this study, SRC can be beneficial for ‘greening’ the urban environment and stabilising contaminated and derelict sites. Survival rather than yield is the key in this goal.

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