The restoration of former opencast mining land to woodland: development and evaluation of a GIS-based tool for strategic planting and management

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by

Janette Lee

A Doctoral Thesis
Submitted in partial fulfilment of the requirements
for the award of
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2004

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Abstract

There is a need for models to assist in the planning and implementation of solutions to environmental problems. Given the spatial nature of these problems, there is scope for GIS to be used as a tool to meet this need. The issue of land restoration following opencast mineral extraction is considered. Time and cost constraints usually place restrictions on the quantity of detailed field data that can realistically be collected and analysed on restoration sites prior to planting. This research determines the value of a rigorous analysis of a limited set of empirical data as a means to informing the decision making process.

The study site selected is located in northwest Leicestershire. Detailed information is collated to describe the site conditions prior to, and subsequent to, mineral extraction. The presence of an adjacent area of undisturbed woodland affords the opportunity for comparison between natural and artificial soil conditions.

Using a combination of field techniques, laboratory analysis, and computer-based modelling, an exploration is made of the factors affecting the success or failure of tree planting within restoration projects. Factors affecting the soil moisture regime are found to play a key role in determining the success of schemes for the establishment of woodland on restored sites. A series of maps are developed to illustrate tree growth potential as constrained by soil thickness and soil structure. Four different 'improvement' scenarios are explored to identify potential areas for remedial action. An analysis of the spatial variation in soil properties can assist in designing planting schemes that reflect the requirements of individual tree species and growth potential indices for alder and larch species are proposed. The hypothesis is accepted that the modelling of soil characteristics can provide additional value to the restoration planning process.
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There are many people to whom I owe a debt of gratitude for their assistance during the years of this research. Firstly, I must thank my supervisor, Professor Ian Reid, not only for the supply of excellent coffee and positive criticism, but also for never failing to be a source of encouragement even during difficult times.

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Many colleagues within the Department of Geography have provided support and advice. Particular thanks must go to Stuart Ashby and Barry Kenny for laboratory and field assistance; and to Mr David Walker, Dr. Val Black, Prof. Helen Rendell and Dr. Jo Bullard, for offering direction, support and guidance over the years. I must also acknowledge the support of friends and colleagues within RSMS who have helped with printing and photocopying, and by giving me time and support to finish this project.

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I owe thanks to my parents, Maureen and Desmond, for encouraging me to follow my dreams and for their unwavering support, regardless of whether my decisions were good ones or bad. To my partner Michael, who has accepted my causing so much disruption to his life, and yet who continues to be supportive and encouraging ...and finally, to Gary: my thanks for being my 'big brother' and always being there for me, and especially, for fighting what life throws at you and coming through it, stronger.
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Chapter 1. Introduction

"I am I plus my surroundings, and if I do not preserve the latter I do not preserve myself."

Jose Ortega y Gasset (1883-1955)

1.1. The importance of the environment

Planet Earth is no stranger to environmental change. In its long history an atmosphere and oceans have appeared, continents have drifted and ice ages have come and gone, and yet life on earth has recovered and developed. Since the rise of humankind, and accelerating over the last century, environmental changes have been occurring from which the earth may not so readily recover (Falconer, 2002). Changes to the climate (Houghton, 1994), to the number of plant and animal species (Eldredge, 1998), to the land use (Vajpeyi, 2001) and to pollution levels (Schnol, 1996) have all been reported and become issues of national and international concern. These changes occur over a range of spatial extents: from global, through regional, to local; and over a range of time scales: from ice ages, through deforestation, to forest fires (Skidmore, 2002).

In terms of land use change, throughout history there has been a tendency to exploit and extract the resources of the earth with little regard being paid to the natural systems which support our existence. Wetlands have been drained; forests have been felled; gaping cavities above and below ground have been quarried; and populations of plants and animals have been decimated. Times are changing, however, and an awareness of the value of natural systems is growing\(^1\). Most people would agree that there are many reasons to protect the environment in order to leave functioning natural resources for future generations.

\(^1\) For example, the Earth Charter (which was approved by the United Nations World Commission on Environment and Development at a meeting in UNESCO headquarters in Paris in 2000) recognises the need to preserve a healthy biosphere, with fertile soil, pure water, clean air, and a rich diversity of flora and fauna (Falconer, 2002).
The focus of this research is on the provision of such a functioning natural resource following the temporary, but devastating, landuse change resulting from opencast coal mining. Site restoration following mineral extraction often leads to a change in landuse and, as will be discussed later in this thesis, those changes may not always be for the better. Geographically, the research centres on the East Midlands coalfield of northwest Leicestershire. The Government of the UK shows a commitment to minimising the adverse impacts from mining activity in a number of ways: through the development of a framework for sustainable development, which includes a section on mineral working (HMSO, 1994; HMSO, 1999); by providing guidance on reclamation processes (DOE, 1996); and by funding research to evaluate the effectiveness of restoration and reclamation schemes (Reeve et al., 2000). In addressing such environmental issues, Eddy (1993) highlights a number of imperatives for scientists (and government) for the future. Among these are the need to monitor changes and to learn more about the past history of environmental change; to build and develop information systems which can provide input to earth system models; and to promote interaction between experts in many disciplines in order to broaden the understanding of both problems and potential solutions. Within a local scale project, these imperatives provide a sense of direction for this research. By looking to understand the (short-term) history of landuse change; by collecting and collating empirical data to underpin an environmental model; and by bringing to bear a multi-disciplinary approach; it is hoped to be able to add value to the decision-making processes affecting site restoration.

The ideals of sustainable land management strive for a balance between human activity and preservation of natural resources, allowing for the activity to continue in perpetuity. A balance is sought between economic growth and environmental quality and viability. Skidmore (2002) identifies three components which must interact in order for this balance to be achieved: policy; participation; and information.
Policy decisions, at national, regional and local levels, can be implemented through legislation; through financial incentives (such as subsidies or tax reductions); through sanctions; and through the designation and protection of sensitive areas. These policies must be accepted; adhered to; and, where possible, welcomed by local actors in the environmental arena: farmers, managers, landowners, stakeholders and the local people.

In order to inform policy and help to invoke participation, there is a requirement for accurate and detailed information, much of which may become the input to some form of environmental model.

1.2. Environmental modelling

Over recent years many researchers have focused on environmental issues and sought ways to solve environmental problems. In many cases this has involved the development and application of some form of environmental model to describe and simulate the processes under investigation (Goodchild et al., 1993).

A model is an abstraction, or a simplification, of reality (Jeffers, 1978, Duerr et al., 1979). In environmental research, a developed model will seek to simulate the function of an environmental process, the motivation often being to explain complex behaviour in the natural system and to derive insight about the physical, biological or socio-economic systems. Once an understanding of these systems has been achieved the models may then also be used for predicting or simulating future conditions as the potential exists to extrapolate through time in order to predict future conditions, or to compare predicted scenarios with conditions observed in the field (Skidmore, 2002).

The ultimate objective for any model is to help in the understanding of, and therefore the management of, a sustainable system. Sustainable development is an approach
which seeks to balance the aims of economic growth with the need to maintain environmental quality and viability. The objective is that, over time, the natural environment will be maintained and preserved: water will not be polluted; soil will not be degraded; and biological diversity will be maintained. At the same time the human demands on the environment, for example for food, shelter and sanitation, can continue to be met. One of the key elements of sustainability is the ability to absorb or to maintain a "... dynamic equilibrium between input and output" (Fresco and Kroonenberg, 1992). This definition of sustainability encompasses the concept of reversible damage. The natural system can be disturbed to meet a particular objective but, for sustainability to be achieved, the disturbance should be able to be mitigated and the system restored at a later date. This approach to sustainability is very applicable when looking at agricultural production systems but can also usefully be seen as a goal when planning any activity involving the management of natural areas, including, as in this research, the field of mineral extraction and restoration following opencast mining.

Environmental models can be developed at a range of scales from a few metres to whole earth, and can be used to assist with a range of tasks including resource management; problem solving; and in the development of policy. Technical or computational constraints can limit the complexity of environmental models, but models need to be targeted to the requirements of the end user. Although it may be an intellectual challenge to develop complex models requiring large volumes of input data, if such models cannot be used in a very real manner by environmental practitioners in the field, then they serve little purpose. As Macmillan (1997) indicates, we should be aiming "... to build a model with which users can play, on the understanding that it can yield useful insights about real decision problems but that those insights are limited by the verisimilitude of the model".

Two logical approaches can be taken when dealing with environmental research. The deductive approach draws a new conclusion from a set of general propositions. General
truths or reasons are accepted and followed to a logical conclusion. The *inductive* approach derives a conclusion from particular facts which appear to serve as evidence for that conclusion. This approach usually takes the form of field data being collected and analysed in order to discover patterns. A relationship between the facts and the conclusion can be observed even if the exact causal mechanism is not understood. Skidmore (2002) summarises the steps necessary to carry out inductive research as:

i. define the problem to be investigated using imagination and discovery;

ii. define the research question to be tested;

iii. based on this question, define the hypotheses to be proven;

iv. collect facts, usually by sampling data;

v. carry out some exploratory data analysis to seek patterns in the data;

vi. confirm, or reject, the hypotheses and draw conclusions.

This method allows for the use of facts (or data) to lead to a conclusion which can be accepted at a stated level of probability.

Both deductive and inductive approaches, and indeed combinations of the two, have been used in the development of environmental models, and researchers have sought to form classifications of models based on the approach adopted and the statistical method employed for data analysis. Burrough (1989) distinguishes between regression and threshold empirical models. Threshold models use boundary values to define inclusion/exclusion from a model and are often expressed using Boolean algebra. Empirical (data-driven) and inductive models can be divided into two types: exploratory and confirmatory. Collected data are explored and, if relationships appear, then empirical methods can be used to confirm rules or processes by statistical analysis (Tukey, 1977). Other modelling approaches have also been adopted. Knowledge driven models are those which use sets of rules to describe relationships between environmental variables, these rules then being used to deduce values for areas where data are missing. Process driven, or conceptual, models use mathematics to describe the factors controlling a process. Stochastic models are employed where the inputs to,
or outputs from, a model are randomly varied and are often implemented using a
neural network model (Skidmore, 2002).

This research project follows a hybrid approach. Empirical data collected in the field
are explored and the relationships found are then confirmed by statistical analysis.
Rules determined in this way are then applied across a wider area in order to predict
values for which empirical data are missing. An attempt is then made to explore the
use of such derived data to predict or model potential future conditions. The necessary
steps to carry out the research are discussed in detail in a later section of this
introductory chapter.

1.3. Land restoration as an environmental issue

The restoration of land and the rehabilitation of ecosystems is one of the few means by
which it is possible to reverse trends of environmental degradation caused by
unsuitable, or unavoidable, destructive land use. Degraded land may be a result of
many actions from the over-cultivation of marginal land; the intensive grazing of arid
lands; or urban and industrial processes. Regardless of the cause of the degradation, a
successful restoration will entail re-establishing the soil, hydrologic and vegetative
characteristics that existed on the site prior to disturbance. In some situations these
characteristics can redevelop over time by means of natural processes (Smith and
Klimstra, 1987). In other situations, where sites have been highly disturbed, there is a
need for active restoration measures such as soil amendment (Hall, 1988; Bending et
al., 1999); artificial drainage (Scullion and Mohammed, 1986; Hodgkinson, 1989); and
re-vegetation (Day et al., 1986). Irrespective of the final land use to be adopted
following restoration, it must be compatible with other forms of land use in the vicinity.
As well as fitting in with the surroundings, site level planning is also a critical step
towards successful restoration, with monitoring and maintenance being of prime
importance. Bradshaw and Chadwick (1980) present a schematic for the development
of a successful restoration scheme which has been reproduced as Figure 1.1.
Additional planting (trees, shrubs etc.)

Maintenance (fertilising, mowing, grazing etc.)

Monitoring (plant growth and soil development)

Seeding (choice of method)

Site preparation (recontouring, drainage, amelioration)

Development of seed mixture (grasses, legumes, other herbs; tree and shrub seed; microbial inocula)

Development of amelioration programme (fertiliser, manures, subsoil, soil etc.)

Formulation of ecological goal for revegetation (in relation to ultimate land use)

Appraisal of site and substrate (climate, physical properties, fertility, toxicity etc.)

Design of operation (orientation of dumps, deployment of overburden, shape of excavation, final landscaping etc.)

Decision on ultimate land use (in relation to environment, social needs, financial return, possible reworking, planning requirements)

Figure 1.1 Steps to successful restoration (from Bradshaw and Chadwick, 1980)
A rigorous planning application is usually required when seeking to change the use of land, and many of the stages of this schema are covered by the legislation governing the planning process. Two of the stages on the diagram are joined by a feedback loop (highlighted in red) indicating that these processes require repeated assessment and action. It is this stage of the remediation process that is pertinent to the current research project. This monitoring and maintenance of a restored site can make the difference between a successful restoration scheme and a failed one. Given the large investment of time, money, and effort which goes into the earlier stages of planning, it would seem wasteful for a restoration project to fail due to a lack of aftercare and maintenance and yet, sadly, this is often the case (Vogel and Gray, 1987; Bending et al., 1991). Goodman (1998) investigates a range of procedures for woodland restoration with costs ranging from £4,000 to £89,000 per hectare and highlights the fact that greater expenditure alone does not guarantee greater survival or greater rate of growth of the trees planted. Goodman (1998) finds that even the most costly woodland scheme in his study had 15% of planted stock failing entirely, and, of the remainder, 23% showed growth of less than 20 cm height per year.

In order to develop restoration strategies which are effective, it is necessary both to be able to predict the rates at which natural processes will effect a measure of recovery and to understand how best to intervene in order to promote that recovery. Conditions found on derelict or worked land can often be detrimental to the establishment of vegetation. For reclamation and restoration to be effective there is a requirement for accurate diagnosis of any constraints that may exist, and for the development of appropriate strategies to deal with those constraints. Failure to address limitations in site conditions can lead to failure of the desired restoration operations and, as a consequence, reduced benefits (commercial, social and environmental) and possibly increased maintenance costs. It is essential, therefore, that reclamation and restoration schemes are designed to provide maximum after-use benefits without incurring unnecessary costs.
The nature of the vegetation in any area will be determined by a complex interaction of effects related to soil conditions; climate; topography; history; and human interaction (Woodcock et al., 2002). Historically, the mapping of vegetation has formed an important part of many voyages of discovery. A more contemporary perspective seeks to map both the 'actual' and the 'potential' vegetation at a given site, where the potential vegetation is that which would occur in the absence of human influence (Box, 1981; Küchler and Zonneveld, 1988). At a local scale, vegetation mapping can be employed to serve the needs of local land management. Land may be utilised as a source of income (food or timber); for recreational use; for the protection of soil; as a wildlife habitat; or as a combination of several of these factors. Whatever the end use, the aim must be one of optimising the desired conditions in order to achieve maximum return both in economic and environmental terms.

1.4. Land use planning using GIS

Land use planning is defined as the making of decisions about the use of land and resources (FAO, 1993) and is carried out in order to achieve the best use of land. Given that conflict often exists regarding competing land uses, the process is often driven by a balance of needs between productivity and environmental sustainability. Where there is pressure on land as a resource, planning activities must seek to make optimal use of that land and any associated resources (Nizeyimana et al., 2002).

Depending on the desired outcome, land use planning can be carried out at national; district; local; farm; or even field level, but at each scale the process will involve: an analysis of the problem; an evaluation of alternative land uses; a decision; and an implementation of the final plan. Any land use planning task has, therefore, an inherent issue of scale and space. Any data collected to support the planning process will consequently have an implicit spatial dimension. The addition of spatial information does not preclude the planner from employing conventional statistical methods to explore and model his/her data, but rather opens up a further, rich, source of potential
data and associated analytical methods. The use of GIS facilitates the use of such methods by providing the capability for storing, manipulating, analysing, and reporting on these data within a spatial framework.

This research project utilises both conventional statistical analysis procedures and facilities from within the sphere of spatial analysis in order to effectively and efficiently store and manipulate both spatial and associated attribute information.

1.5. Research objectives

There is a need for models to assist in the planning and implementation of solutions to environmental problems. Given the spatial nature of these problems, there is obviously scope for GIS technology to be used as a tool to meet this need. Taking these two factors on board, this research takes as its focus the contemporary environmental issue of land restoration following opencast mineral extraction. Using a combination of field techniques, laboratory analysis, and computer-based modelling, an exploration is made of the factors affecting the success or failure of tree planting within restoration projects. Using the steps set out above from Skidmore (2002), the project can be described as follows:

i. the problem to be investigated is that many restoration programmes following opencast mineral extraction fail to reach their potential as productive sites. Some regions within restored sites show high levels of success while other regions show failure. The identification of this problem leads to the following questions being asked:

ii. why does this differential pattern of success exist, and, can anything be done to improve the levels of success across any given restoration project? Planting schemes for restoration projects are designed to be site-wide with little consideration being given to within-site variation in conditions. Given that
most restoration projects following open-cast mining cover a small geographical area, it is unlikely to be differences in climate, altitude or local factors (such as proximity to roads or industrial centres) that are leading to these patterns of success or failure.

iii. the first hypothesis to be tested is, therefore, that differences in soil properties within the restored area are causing variation in the patterns of tree success. If a relationship is found to exist between soil properties and the patterns of tree success, further exploration of the data will seek to show that the measuring (or modelling) of the spatial distributions of soil parameters can provide information from which planting schemes can be designed which make optimal use of site conditions and offer the greatest potential for return on investment.

The second hypothesis to be tested is that the modelling of topsoil characteristics can provide additional value to the restoration planning process.

iv. in order to test the hypotheses, data are collected for a range of topsoil properties which may be affecting vegetation growth. These data are collected for a range of areas across the site which show differing levels of vegetation success.

v. once collected, these data are examined in order to determine whether or not they offer any level of explanation of the spatial patterns of vegetation success. Inter-relationships between soil properties are explored as are the relationships between the soil properties and the growth rates of a range of tree species. Analysis and modelling of the data seek to explore whether predictions about site conditions can be made for areas for which no empirical data are available.

vi. if satisfactory explanations are found then the null hypotheses can be rejected and the model proposed as a means for improving the design of planting schemes by taking account of within site variation in conditions.
Literature review: the impact of opencasting on soils and vegetation

Site selection

Surveys: topography and tree density

Identification of sample regions and points

DATA COLLECTION

Volumetric topsoil moisture
Chemical analysis of topsoil
Topsoil thickness
Topsoil shear strength
Topsoil bulk density
Tree diameter

GENERATION OF MODELLED SURFACES

Volumetric topsoil moisture
Topsoil thickness
Tree diameter
Topsoil shear strength
Topsoil bulk density
Tree success

MODEL TREE GROWTH

Figure 1.2 Overview of research design.
1.6. Thesis structure

The main foci of this research are:

- to explore factors affecting the success of tree planting on restored ground following mineral extraction using opencast methods;
- to determine a method for optimising the level of planting success, based around a programme of well-planned data collection, and making use of a GIS to model and manipulate these data.

Time and cost constraints usually place restrictions on the quantity of detailed field data collection that can realistically be carried out on restoration sites prior to planting. For that reason, this research attempts to determine whether a limited set of empirical data, rigorously analysed and modelled, can offer valuable assistance to the decision making process. An overview of the research design can be seen in Figure 1.2.

This initial chapter has introduced the importance of the environment with particular emphasis on land restoration as an environmental issue. The concepts underpinning environmental modelling have been explored and the potential role of GIS within land use planning has been discussed. The research direction has been outlined and the objectives set. Chapter 2 presents a brief history of opencast mining in Great Britain and looks at the legislation relevant to the planning of, and restoration following, opencast mining operations. Given that opencast mineral extraction and subsequent restoration leads to changes in soil properties, Chapter 3 investigates the role of soil as a medium for plant growth and compares the physical and chemical nature of disturbed and undisturbed soils. The available methods for measuring and monitoring a range of soil parameters are discussed with the most suitable options for this research project being identified and justified. Chapter 4 explores the use of GIS for land use planning and discusses a range of statistical and methodological procedures to be employed in the analysis of data collected in the field. Chapters 5 and 6 discuss the selection of the field site for the research and detail the design and implementation of the data collection regime. Chapter 7 explores the patterns found in the data while Chapter 8 investigates those patterns in a wider areal context and explores how the data can best be used to inform decisions regarding the restoration process. Finally, Chapter 9 draws some conclusions, sets these in the context of similar research, and makes suggestions for ways in which the research can be developed and taken forward in the future.
Chapter 2. Opencast coal mining in Great Britain

"We do not inherit the earth from our parents, we borrow it from our children"

Kenyan proverb

2.1. A brief history

The process of opencast mining is a relatively short term procedure, usually lasting between one and ten years, employed to obtain access to shallow, often narrow, seams of coal which are not readily mined by conventional deep mining methods (Grimshaw, 1992). In the UK, opencast mining is found in areas where the coal seams either reach the surface (known as an outcrop), or exist at relatively shallow depths (Beynon et al., 2000). Figure 2.1 shows the distribution of these shallow deposits of coal. Opencast mining is often also employed as a means by which to recover any coal remaining after the closure of deep mine workings (Grimshaw, 1992).

The British opencast industry, although now well established and efficient, has only been in operation for just over fifty years as it came about as an emergency measure during the Second World War (Jackson, 1991). By contrast, in the United States, coal was first dug by a steam shovel as early as the 1870s with the development of purpose built stripping shovels leading to large-scale surface mining by 1911 (Grimshaw, 1992). In the early years of the 20th century surface-mined coal was sometimes obtained as a by-product of the exploitation of other materials such as clay. There had also been a certain level of coal extraction from shallow surface workings of outcrops where the coal was hand-dug or worked by means of bell-pits (see Figure 2.2; from Grimshaw, 1992). Local outcrops were exploited during strikes or lock-outs at collieries for example during the strikes in 1926 (Grimshaw, 1992).
Figure 2.1 Areas of shallow coal deposits in the UK (from Beynon et al., 2000)
The long-established deep coal mining industry had traditionally met the country's need for coal and seemed to perceive the opencast industry as competition, rather than as being complementary to its own activities. The fact that opencast and deep-mine workers have always been represented by different trades unions serves to illustrate this perceived division between the industries (Beynon et al., 2000). Within the United Kingdom, the opencast industry did not develop until the 1940s when, during the early years of the Second World War, there was a significant drop in the production from the deep mines which had suffered shortages of manpower and other resources. Prior to the war, opencasting had not formed part of long term plans for coal production and distribution. Taking part in the Central (Coal Mines) Scheme (Amendment) Order debate in May 1941, Albert Braithwaite, a businessman with interests in collieries and quarries and Member of Parliament for the East Riding of Yorkshire, called for a return of trained colliers from the armed forces (Braithwaite, 1941). The Government initially refused to release servicemen, leading Braithwaite to contemplate other means of boosting coal production. As a consequence he proposed the use of civil engineering companies to exploit surface coal measures, an idea that could be effected rapidly, employing few people with less specialised skills. An acceptance of this approach led to the creation of the opencast coal mining industry in mid-1941 and a search for easily accessible shallow coal reserves. By October 1941, potential sites had been identified.
in Fife, Yorkshire and Warwickshire and an eleven point plan for their exploitation 
was drawn up:

- obtain drilling rigs to prove and sample coal;
- obtain entry on to the land;
- calculate quantities of coal and overburden;
- determine the nature and extent of hard rock;
- only work simple seams (no dirt partings) of greater than 3 feet thickness;
- obtain excavating and transportation plant;
- obtain rights to disturb land, remove coal and store overburden;
- obtain clearance that any underground workings would not be affected;
- construct railheads and central coal handling plant;
- undertake to restore all land taken for coal;
- recruit necessary skilled personnel.

Even in these early days of opencasting, restoration of land following mineral 
extraction was an important consideration. In 1941, restoration to agriculture was 
particularly important as it was important to maintain food production during the war 
years. The Wellington Journal for 11th October 1947 reports a visit to opencast coal 
sites in the Wrekin area which had been re-seeded that summer under the auspices of 
the Shropshire War Agricultural Executive Committee:

'... The working of the various sites and the methods used for restoration of the land after the removal of the 
coal, were explained, and questions were put by the members of the party as to whether the huge excavations 
were justified by the results. They were told that the actual cost of the coal per ton would prove much less than 
various reports had anticipated.

... On the subject of the length of time needed for the removal of the top- and sub-soil to get down to the coal 
itsel itself and then for the restoration of the land afterwards, the visitors were told that once a seam had been 
reached one man working with a mechanical shovel could remove no less than 500 tons per eight hour shift, 
and experienced mining labour was not needed. A few skilled mechanical operators and a sprinkling of other 
labour was all that was required.

... Regarding the effect on the land, it was stated that former difficult scrub land, having been restored and re-
seeded, gave apparent promise of good pasture, and the party actually saw one site upon which stock was 
grazing.'

Work on the first two 'official' opencast sites began in October 1941 at the Bedgreave 
Wood site in Yorkshire and, in November 1941, at Dordon near Atherstone in 
Warwickshire (Grimshaw, 1992). By March of the following year these two sites were 
producing 1,000 tons of coal a day yet employing only 40 people. In December 1942 a 
newly formed Directorate of Opencast Coal Production (DOCP) was formed within the 
Ministry of Works and Planning which took over control of opencast operations from
the Ministry of Fuel and Power (Beynon et al., 2000). The tasks of the DOCP were returned to the Ministry of Fuel and Power in April 1945 and remained here until the National Coal Board took on the responsibility for opencast (along with deep mining) operations in April 1952, albeit with a largely autonomous 'Opencast Executive'. The renaming to British Coal in 1987 and the removal of the 'Executive' in 1990 led to British Coal Opencast (BCO) being the inheritor of the responsibilities of the original DOCP (Beynon et al., 2000).

Initially, rapid progress was made within the opencast industry. By the end of 1944, a total of 419 sites had been opened with output rising from 4.4 million tons in 1943 to 8.6 million tons in 1944. By the end of the war in 1945, there were around 150 sites in operation, employing over 7,000 people, although still only contributing about 5% of the total coal output for the country (Grimshaw, 1992). The production figures for opencast extraction are shown in Figure 2.3.

Figure 2.3 Opencast Coal Production, 1941-2004

\(^1\) figures from www.coal.gov.uk
Opencasting was seen as a temporary measure and has constantly been susceptible to changes in the political, social and economic climate. In the autumn of 1946, the Minister of Fuel and Power stated that opencasting would cease by 1948 (Grimshaw, 1992). This did not come about as deep mine output was still unable to meet post-war demands, a situation exacerbated by the weather conditions during the "Big Freeze" of 1947. In 1959, when a downturn in the market for coal led to potential job losses, the decision was taken to reduce levels of opencasting rather than those of deep mining. The 'sunshine miners' of the opencast industry were viewed by the National Coal Board as being on the periphery of the business of coal production, in contrast to the deep mines whose workers were well served by an active and vocal National Union of Mineworkers (Grimshaw, 1992). Government policy at the time did not permit the opening of new opencast sites other than for the production of special coals e.g. anthracite. Some sites with long contracts remained operational but many others had operations curtailed. The 1967 White Paper on Fuel Policy imposed more restrictive conditions on both amenity and job creation factors which disadvantaged the opencast industry (HMSO, 1967). However, by the beginning of the 1970s, the deep mines were having difficulty in meeting the demand for coal. The ease with which opencast coal was fed into normal distribution channels following the 1972 coal strike showed the potential for cost effective opencast extraction. The 1974 Plan for Coal recognised this potential and projected a gradual increase in opencast production to 15 million tonnes per year by the mid-1980s (National Coal Board, 1974). This target was achieved ahead of schedule, in 1981. The original plan had been that opencast output would fluctuate to meet national coal requirements, depending upon the output achieved by the deep mining sector. This plan became increasingly difficult to implement as the opencast industry continued to grow, with sites increasing in size and being worked for increasingly long periods. Until March 1984, planning permission for surface coal mining in the United Kingdom was granted by the Secretary of State for Energy but since then it has passed to the Mineral Planning Authorities (often the County Councils) of each region (Mineral Planning, 1988; Rutherford and Peart, 1989). The number of successful planning applications fell by about a third following this involvement by the County Councils (Grimshaw and Smith, 1988). Nevertheless, by
1992, BCO was operating approximately sixty sites; employing some 15,000 people; and producing around 17 million tonnes of coal annually (Beynon et al., 2000).

2.2. Regulations and restoration

Until 1958, when the Opencast Coal Act was passed, opencasting operated under Defence Regulations which gave the industry a unique legal position in that its activities were not subject to the Town and Country Planning legislation. When the Opencast Executive applied for permission to work a site, the authorisation was obtained from the Minster of Fuel and Power and not from the local planning authorities or the planning minister. The support of the planning authorities was often sought though, in order to increase the chances of a successful outcome for the application (Beynon et al., 2000).

There have been ongoing efforts to find a balance between the environmental damage caused by opencasting and the national requirement for low cost fuel. As early as 1943, the Ministry of Works imposed the responsibility on the DOCP to return ground to a condition fit for agricultural purposes. This involved the refilling and consolidation of the overburden and the replacing and levelling of topsoil. As little as 150 mm of topsoil could be spread, often with no requirement for the removal of large stones or debris (Grimshaw, 1992). Thin topsoil, an absence of subsoil and a lack of artificial drainage often led to rapid problems with agricultural productivity and a review of restoration methods was undertaken in 1947. A code of practice issued by the Ministry of Agriculture, Fisheries and Food (MAFF) in 1951 recommended the stripping and storing of topsoil and subsoil and a standard rehabilitation programme for up to 5 years following extraction (MAFF, 1951). It has long been recognised that a high level of planning and care is required if utility is to be regained from land following mineral extraction. This has been reflected in restoration policies and practices which have developed rapidly since the latter part of the 1970s. Environmental statements are now standard practice. Current legislation requires that land being worked for minerals must be reclaimed at the earliest possible date to a
beneficial after-use. It is imperative, therefore, that the reclamation process result in land conditions which are capable of supporting that after-use.

In 1981, the Town and Country (Minerals) Act saw a formalisation of the legislation for reclamation, restoration and aftercare of mineral workings. The planning authorities in England, Wales and Scotland were given the power to impose aftercare conditions when granting permission for mineral workings where the proposed end use of the restored land was agriculture, forestry or amenity. This legislation came into effect for all new minerals permissions granted after 22 February 1982. The powers of the 1981 Act have now been subsumed into Schedule 5 of the Town and Country Planning Act 1990 (for England and Wales) and Schedule 3 of the Town and Country Planning (Scotland) Act 1997. The Department of the Environment, Transport and the Regions (DETR\(^1\)) defines reclamation as ‘operations associated with the winning and working of minerals that are designed to return the land to an acceptable environmental condition and to a condition suitable for the after-use’ (DETR, 2000). Reclamation therefore encompasses restoration (the placement, ripping and grading of soils); events taking place before and during mineral extraction (e.g. the stripping, storage and protection of soils); operations carried out after extraction (e.g. contouring, drainage schemes, the creation of planned water features); and aftercare. ‘Aftercare’ refers to operations which are carried out following replacement of the full soil profile, such as cultivation, drainage, fertilisation and planting, which bring the land up to the necessary standard to achieve the proposed after-use.

The legislation has provided a framework through which progress in restoration and aftercare can be monitored and has led to benefits and improvements in the overall standard of reclamation. However, the procedures are not followed uniformly across the country and work is ongoing in order to determine ways in which improvements can be made (DETR, 2000).

\(^1\) now the Department for Environment, Food and Rural Affairs (defra)
2.3. Restoring land for forestry

Opencast coal working in its present form has been occurring in Great Britain for over fifty years. Most of the worked sites have been returned to agriculture although in cases where conditions have been restrictive, for example if top soil has been lacking, areas have been returned to forestry (Binns, 1983). Where forestry is the proposed after-use for a minerals extraction planning application, there is a statutory requirement for consultation between the Minerals Planning Authority (MPA) and the Forestry Commission (FC). In the legislation, ‘forestry’ is defined strictly as ‘the growing of a utilisable crop of timber’, meaning that this statutory consultation does not apply to any after-use of amenity woodland. The Minerals Planning Guidance Note 7, The Reclamation of Mineral Workings, 1989 (MPG7) recommends that such consultations be carried out.

Given the increase in the proportion of land being reclaimed for amenity use, which includes amenity woodland (Figure 2.4), MPAs are being encouraged to consult with a range of organisations (including the Countryside Agency, the Forestry Commission, English Nature and the Environment Agency) in order to obtain views and expertise on suitable aftercare conditions and schemes for amenity use.

The DETR (2000) report highlights the fact that in the early 1980s the available knowledge pertaining to forestry restoration was at a much lower level than that which was available for agriculture. The intervening years have seen an increase in expertise, much work having been carried out by the Forestry Commission Research Division (Moffat and McNeill, 1994), in turn providing an important contribution to the updated 1996 edition of The Minerals Planning Guidance Note 7. The guidance notes require that, if forestry is the proposed after-use, then the planning application must include information regarding the nature of the deposit to be worked. This must include details of the mineral to be extracted; any prospecting or exploratory work to be carried out; details as to the nature, thickness and quantity of topsoil, subsoil, overburden and mineral to be extracted; information on waste materials; the physical and chemical
properties of the mineral to be extracted; the geology and topography of the site, including details of land stability, water table, ground conditions and surface water drainage.

Figure 2.4 Proposed after-uses of mineral workings in England subject to aftercare conditions (from DETR, 2000).

The planning application must also include details regarding material processing, including a description of the nature and quantity of processed waste and the method of disposal. Restoration and aftercare details should be provided describing the intended after-use; contours and final levels for the site; soil materials to be used; and the time-scale of operations. Details of any filling materials required, of proposed
drainage and of permanent water areas, should be provided alongside information regarding the provision and monitoring of aftercare procedures. Plans and drawings must be included to show details of the proposed levels of areas to be worked; the surface area, height and location of mineral stockpiles and of topsoil, subsoil and overburden mounds; and details of landscaping and restoration to the final levels for the restored site. Further to the requirements of The Minerals Planning Guidance Note 7 (MPG7), the Environment Act (1995) includes the stipulation that all extraction sites be reviewed every 15 years in order to ensure that all sites are reclaimed to the prevailing standards of the day (Bending et al., 1999).

2.4. A role for 'precision forestry'?

Arable fields are not uniform in their topography or in the properties of their soils (Warrick and Nielson, 1980; Brubaker et al., 1993; Wade et al., 1996). The environment both above and below ground can vary considerably across a small area (Warrick & Nielson, 1980; Patterson & Wall, 1982; Burrough, 1993). Despite this variation, conventional agricultural practice considers a field as uniform and applies farming treatments at a constant rate. Using a precision agriculture approach for site specific management, any field being worked can be broken down into smaller units and decisions taken based on the characteristics of those units. Thus, operations can be targeted to areas of need e.g. herbicide can be applied only in areas where there are weeds and fertiliser can be applied only in areas of lower yield. An assessment can also be made of physical parameters e.g. Fulton et al. (1996) investigated soil compaction levels in order to vary tillage depths across a site. These 'spatially variable field operations' (Stafford et al., 1991) reduce both costs and environmental impacts.

Precision agriculture is a relatively new concept in farming practice (Westervelt and Reetz, 2000). It is a comprehensive system designed to optimise agricultural production and has five major objectives:
• to increase production efficiency;
• to improve product quality;
• to increase the efficiency of chemical use;
• to conserve energy;
• to protect soil and ground water.

In order to succeed, precision agriculture relies on three components: information, technology and management.

The information can include such things as crop characteristics, soil properties, fertility requirements and details of weed and insect populations. Modern technology, in particular computer-based databases, spreadsheets and geographical information systems allow for the organisation, storage and retrieval of the relevant information. Management combines these two components of information and technology into a comprehensive system to help in the interpretation of the data and allow for optimal production decisions to be taken.

Although predominately used as a management approach for arable farming, there may be a role in other areas. When a site is to be restored to woodland following mineral extraction, it is necessary to include a high level of detail in the planning process regarding the procedures to be employed during restoration. One component of any planning application will be details of the planting procedures to be undertaken at the restored site. These will include details of species to be planted; approximate timings for planting; and a plan of the planting layout to be employed. Given the heterogeneous nature of soil, and in particular soil on restored sites (which have been stored in mounds for prolonged periods and been subjected to heavy trafficking by machinery), there may be value in carrying out a detailed site survey following reclamation. An assessment of topographic variation and a range of soil physical and chemical parameters, interpreted in the light of information regarding conditions favoured by the required tree species, could provide the data for a 'precision
restoration' model. A planting regime could then be designed to take account of any spatial variability. In the same manner in which precision agriculture has developed an assessment of in-field variability and a consequent modification of procedure to take account of that variability in order to optimise yield, so with the replanting of restored soils for woodland, an assessment of soil variability could provide a means of optimising the success of a woodland restoration programme. The success of restoration to forestry may be best judged by comparing the progress made by the post-extraction soil towards the 'normal' pre-extraction conditions; but, in practice, success will be judged mainly on the growth of the trees themselves (Wilson, 1985) and of the acceptability of the end product to the local community (McRae, 1989).
Chapter 3. Soil properties and their effect on vegetation growth

"As soils are depleted, human health, vitality and intelligence go with them."

Louis Bromfield (1896-1956)

3.1. Introduction

Soil properties have a direct impact on soil biota in the extent to which they encourage or constrain growth. Many, and diverse, impacts result from changes in supply of nutrients, moisture and air. There are a number of other chemical and physical controls which may also affect vegetation growth, usually through their associated effects on these supplies of air, moisture and nutrients. These controls are central to all soil environments, both those with profiles which have developed naturally over time by means of weathering, translocation and accumulation of soil materials and those, such as would be found on restored opencast sites, which have been directly impacted by man and their profiles artificially constructed.

The handling and storage of soil during mineral extraction can lead to a deterioration in the physical conditions. Problems have been encountered due to changes in a range of soil properties. On restoration, these soils can also show significant changes to their chemical properties. These changes in soil properties often lead to conditions which pose difficulties to the establishment of vegetation. Cleveland and Kjelgren (1994) report that by 1988, of approximately 77,000 ha of land eligible to be reclaimed to trees, only 6% met the mandated stocking rates. This low success rate has largely been attributed to problems of compaction imposing stresses limiting to tree growth; research has shown that soil properties differ in many ways between natural and restored soils.
3.2. Soil physical properties

In his description of soil as a medium for supporting plant growth, Hillel (1971) identifies constraints on the physical (as well as the chemical) fertility of a soil. Soil structure is defined as the arrangement of particles and pores in soils (Rowell, 1994). A well structured soil will have adequate pore space to facilitate the storage, and movement, of water. A soils ability to retain moisture can impact on plant growth (especially in times of drought) while the infiltration capability of a soil is important in respect of moisture availability to plants. In order to support vegetation, soils require an air-water balance that provides adequate drainage while maintaining a sufficient supply of moisture for plant growth (Ellis and Mellor, 1995). A balance must be achieved whereby surplus water drains rapidly from the surface to prevent standing water (and the consequent development of anaerobic conditions) while at the same time ensuring that infiltration is adequate to sustain vegetation growth. Brady (1990) identifies soil structure and soil texture as being important physical properties of the soil, affecting the ability of the soil to supply nutrients and to supply the air and water necessary for root activity. The soil structure should be such that drainage through the soil does not lead to a loss of pore space as silt and clay particles are transported through the soil profile. Bending et al. (1999) divided the physical properties used to describe soil (or soil-forming materials) into two subgroups: structural properties; and behavioural properties, as shown in Table 3.1.

3.2.1. Texture

Texture is the most fundamental of all soil properties. Soils are classified according to the proportions of sand (60 - 2000 µm), silt (2 - 60 µm) and clay (< 2µm). Along with organic matter content, texture is one of the predominant determinants of the water holding capacity of a soil (Brady, 1990). Sandy soils have a pore size distribution which favours the free movement of air and water but, as a consequence have a low capacity for holding water and can tend towards droughtiness. The lack of aggregation between particles makes sandy soils susceptible to water and wind erosion. Clay soils tend to inhibit the passage of moisture through a soil, and may often be poorly drained,
poorly aerated and susceptible to compaction (Cruickshank, 1972), although the formation of cracks and fissures as clay soils are dried can offer a means whereby moisture can reach lower levels within the soil profile.

Table 3.1 The physical properties of soils (from Bending et al., 1999).

<table>
<thead>
<tr>
<th>Structural properties</th>
<th>Behavioural properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture and stoniness</td>
<td>Soil water</td>
</tr>
<tr>
<td>Bulk density</td>
<td>Infiltration</td>
</tr>
<tr>
<td>Consistence</td>
<td>Hydraulic conductivity and permeability</td>
</tr>
<tr>
<td>Air permeability</td>
<td>Heat capacity, thermal conductivity and diffusivity</td>
</tr>
<tr>
<td>Aggregate size distribution, stability and strength</td>
<td>Strength</td>
</tr>
<tr>
<td>Porosity, void ratio, air filled porosity, pore size distribution</td>
<td></td>
</tr>
</tbody>
</table>

Silty loams have the most potential for productivity as they tend to aggregate well, be well drained and aerated and have good water holding capacities (Williams et al., 1983).

3.2.2. Bulk density

Bulk density relates to the combined volume of both solids and pore spaces within a soil, with soils that have a high proportion of pore space having a lower bulk density. Normal ranges of bulk density have been reported for clay, clay loam and silty loam as being from 1.0 Mg m\(^{-3}\) to 1.6 Mg m\(^{-3}\); for sand and sandy loam as 1.2 Mg m\(^{-3}\) to 1.8 Mg m\(^{-3}\); while compact subsoils may have bulk densities of 2.0 Mg m\(^{-3}\) or greater. This high level of compaction (essentially indicative of an absence of macropores within the soil) has been found to constrain root growth at bulk densities of 1.6 Mg m\(^{-3}\) and above (Brady, 1990). This increase in bulk density at depth within the profile may, in part, be
due to lower organic content, less root penetration, and compaction from the weight of overlying layers. Cropping and soil management procedures will effect changes in soil bulk density. McIntyre et al. (1987) found that clear-cutting of forests led to increased bulk density in the surface layers of the soil (to approximately 8 cm depth). Research in Canada has clearly shown that intensive cropping and cultivation leads to increased bulk density of topsoil, whereas the addition of large amounts of crop residue or farm manure will lower bulk densities of the surface soil layers (Tiessen et al., 1982). High bulk density and low porosity have been found to lead to slow percolation of water through the soil profile and seasonal waterlogging (King, 1988). Soils experiencing this tendency towards saturation under wet conditions are prone to the development of anaerobic conditions, associated nitrogen loss and the consequent difficulties in sustaining vegetation growth (White, 1987).

3.2.3. Consistence

Soil consistence describes the resistance of a soil, at various moisture contents, to mechanical stress and is generally reported for wet, moist and dry soil conditions using a range of terminology as shown in Table 3.2.

<table>
<thead>
<tr>
<th>Wet soils</th>
<th>Moist soils</th>
<th>Dry soils</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stickiness</strong></td>
<td><strong>Plasticity</strong></td>
<td></td>
</tr>
<tr>
<td>Nonsticky</td>
<td>Nonplastic</td>
<td>Loose</td>
</tr>
<tr>
<td>Slightly sticky</td>
<td>Slightly plastic</td>
<td>Very friable</td>
</tr>
<tr>
<td>Sticky</td>
<td>Plastic</td>
<td>Friable</td>
</tr>
<tr>
<td>Very sticky</td>
<td>Very plastic</td>
<td>Firm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Very firm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extremely firm</td>
</tr>
</tbody>
</table>

Coherence increases from top to bottom in each column

The soil consistence is of practical use when working soils. It can be an effective indicator of the potential for soil compaction by heavy machinery either for farming, or for mining, operations.
3.2.4. The effect of restoration on soil physical factors

In situations where chemical toxicity and soil deficiency are not a problem, Stewart and Scullion (1989) identified the loss of natural structure as being the major limitation to the successful restoration of worked soils. Soil texture, bulk density and organic matter content are all factors which reflect the soil structure and the volume of soil macropores. Soil structure directly affects the process of soil aeration which is vital in controlling the levels of oxygen and carbon dioxide within the soil. These gases are essential components of respiration and photosynthesis with the process of soil aeration allowing the exchange of these gases between soil and atmosphere. Most plants require that a minimum of 10% of soil air be composed of oxygen, with nitrogen and carbon dioxide being the other gaseous components. A well-aerated soil will ensure a sufficient supply of oxygen to facilitate healthy plant growth while ensuring that concentrations of carbon dioxide and other potentially toxic gases (such as methane) do not reach excessive levels (Brady, 1990).

Research carried out by Malik and Scullion (1998) showed that damage to the soil structure can occur during the time the soil/subsoil is stored prior to restoration. Stripping and removal of the soil can lead to compaction and loss of structure, reduced aggregate stability and changes in the nature of organic materials. They also noted reduced microbial activity and a tendency for anaerobic conditions to develop at depth within the storage mounds. Armstrong and Bragg (1984) found that aggregate stability and soil porosity in restored soils were low when compared with similar unworked soils. Similarly Bussler et al. (1984) noted vegetation growth being limited by compaction, poor drainage and restricted root depths.

King (1988) highlighted problems with compaction and decreased subsoil permeability on restored opencast mine soils, a fact supported by Davies et al. (1992) who recognised that decreased porosity and hydraulic conductivity can lead to a decrease in the available water capacity of the soil, which in turn can restrict vegetation growth. The water holding capacity of a soil is affected by a number of factors including the
particle and pore size distributions, bulk density, organic matter content and hydraulic conductivity. Redistribution of rainfall into the subsoil is impeded if fissures and pores are destroyed and so restored soils tend to shed winter rainfall rapidly with little recharge of the subsoil water reserves (Jarvis et al., 1984). Although the findings of Davies et al. (1992) showed textural similarities between disturbed and undisturbed sites they noted a greater bulk density and a lower available water content in the soils on restored sites. Scullion and Malinovszky (1995) found that waterlogging of soils was a significant factor in restricting tree growth. Research by Scott-Russell (1977) showed that anaerobic conditions in soil as a result of waterlogging reduced the ability of plants to absorb nutrients. Waterlogging has been identified as major cause of restricted vertical root growth (Bending et al., 1991), with high bulk density and high percentage of stones also inhibiting root penetration.

Moffat and McNeill (1994) noted that almost all tree species required an aerated root zone in order for proper root functioning to occur, exceptions being poplars and willow which are able to obtain oxygen via the plant stem. This requirement means that rooting is mostly restricted to the aerobic zone in the upper soil layers. If this aerobic layer is too shallow then summer drought conditions can easily occur.

Vegetation instability is also increased if rooting depth is restricted. Penetration resistance, as measured by a penetrometer, has been used as an indicator of potential root penetrability. Research by Taylor et al. (1966) and Cockroft et al. (1969) found that roots are restricted in soils with a penetration resistance of force greater than 30 N.

In their work on tree growth on two restored opencast sites in Wales, Scullion and Malinovszky (1995) identified areas of good growth as those having soils with greater proportions of pore space (i.e. being less compacted) and with higher proportions of organic matter than were found in areas of poor growth. In terms of pore space, sites showing good tree growth (for Alnus spp., Betula spp. and Quercus spp.), had on average, 1.1% greater pore space than sites showing poor tree growth. Some sites
showed nearly 3% greater pore space when comparing sites of good tree growth with those of poor growth. Organic matter (estimated by loss on ignition) was found to be greater, by between 0.09 and 1.28 grammes per 100 cubic centimetres of soil, at sites of good tree growth when compared to sites of poor growth (Scullion and Malinovszky, 1995). This supports the earlier findings of Dawkins et al. (1985) who observed that opencast sites with better tree growth usually had soils with a higher content of organic matter. Soils to be restored for woodland and forestry use must have an adequate thickness of material to allow roots to develop normally. As well as channelling water and nutrients, the rooting system provides anchorage for the growing tree. A minimum thickness of 1000 mm of soil or soil-forming materials is recommended by Moffat & Bending (1992). Increasing thickness of soil was found by Perry (1982) and Scullion and Malinovszky (1995) to correlate with better tree growth. Andrews et al. (1998) supported this with their findings that soil thickness is the most significant variable affecting tree growth. They employed two measures to ascertain soil thickness: the use of a penetrometer and measurement from a soil pit. Penetrometer readings did not supply an accurate enough measure of available rooting depth due to interference by rock fragments in the soil.

Regarding the relation between root penetration and soil compaction Bending et al. (1999) recommended that, in order to promote surface rooting, the top 500 mm of the restored soil profile should have a minimum bulk density of 1.5 Mg m\(^{-3}\) with a maximum of 1.7 Mg m\(^{-3}\) in the lower profile. Restoration of landform both by loose tipping and complete cultivation can achieve these densities, but the more traditional technique of utilising motor-scrapers and ripping, although initially loosening the soil to the required densities, has been found to lead to rapid and severe soil re-compaction. Moffat and Bending (2000) concluded that the poor performance of many planting schemes on restored sites can be attributed to a failure to recognise or address the issue of compaction.
In terms of the physical landscape, slope was found by Andrews et al. (1998) to be a significant factor affecting tree growth, with the best growth to be found on steeper slopes within restored sites. Although appearing to oppose the expected findings on natural soils, where increased slope might imply increased runoff, leading to greater erosion and shallower soils, on restored sites steeper slopes are more likely to be spared the compaction associated with machinery traffic and therefore have better aeration, lower bulk density and more efficient drainage. Research by Andrews et al. (1998) found a strong negative correlation between slope and bulk density and, due to the limitations of their penetrometer readings, they used slope values as a surrogate for bulk density in their statistical analysis.

Slope is an important parameter in relation to the planned use of restored sites. Harris et al. (1996) identified slopes of up to 35° as being suitable for forestry, with limits of 15° for pasture and 5° for crops. Moffat and McNeill (1994) indicated slopes of between 5° and 6° as being necessary for the efficient removal of excess water. In wetter areas, the implementation of a 'ridge-and-furrow' type of cultivation can aid in the movement of water across an area by reducing waterlogging on the ridges and providing a greater depth of aerated soil to facilitate root growth. This same action in drier areas, however, might lead to poor growth on ridge tops due to a greater soil water deficit in the summer months. Aspect is found to have a marked effect on the micro-climate of an area, especially in regard to soil temperatures during summer months (Moffat and McNeill, 1994), these differences becoming more pronounced as slope angle increases. Higher temperatures on south-facing slopes in spring may give some phenological advantage, but Reid (1977) showed that this may be attenuated by an increased likelihood of drought conditions in summer.

From an analysis of the available literature on soil restoration, the decision was taken to focus this research on a number of key physical soil properties which have been found to be of significance in affecting the establishment of vegetation on restored sites. To that end, a site survey was set up to obtain details of a range of properties of
the topsoil layer. These included thickness of topsoil horizon; bulk density; particle size distribution; Atterberg limits; shear strength and volumetric soil moisture. Details of the sampling regime employed are presented in Chapter 6.

3.3. Chemical properties of natural and restored soils

The major components of the soil (minerals, organic matter, water, and air) interact in the provision of essential nutrients for plant growth. This growth is dependent on the supply of both macro-nutrients, of which relatively large quantities are needed, and lesser quantities of micro-nutrients (Mengel and Kirkby, 1982). Among the required macro-nutrients are calcium, potassium, nitrogen, phosphorus, magnesium and sulphur while micro-nutrients include iron, manganese, zinc, copper and chlorine. Table 3.3 shows the figures found by Bradshaw and Chadwick (1980) to be the normal ranges for a variety of nutrients essential for adequate plant growth.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range (low – high)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5.0 – 7.5</td>
</tr>
<tr>
<td>Cation Exchange Capacity</td>
<td>10 – 30 meq 100 g⁻¹</td>
</tr>
<tr>
<td>Exchangeable K</td>
<td>10 – 30 mg 100 g⁻¹</td>
</tr>
<tr>
<td>Exchangeable Ca</td>
<td>50 – 200 mg 100 g⁻¹</td>
</tr>
<tr>
<td>Exchangeable Mg</td>
<td>5 – 30 mg 100 g⁻¹</td>
</tr>
<tr>
<td>Exchangeable P</td>
<td>0.5 – 2.0 mg 100 g⁻¹</td>
</tr>
<tr>
<td>Exchangeable NH4-N</td>
<td>0.2 – 2.0 mg 100 g⁻¹</td>
</tr>
<tr>
<td>Exchangeable NO3-N</td>
<td>0.2 – 2.0 mg 100 g⁻¹</td>
</tr>
</tbody>
</table>

Bradley (1990) identified problems of retarded plant growth due to three different nutritional scenarios: firstly, where insufficient quantities of these nutrients are available; secondly, if the nutrient supply is unbalanced; and thirdly, if the nutrients are
not in a readily accessible form for uptake by plants. Positively charged plant nutrients (cations) when adsorbed by clays and organic colloids are not immediately available for uptake by plants. Cation exchange is the process whereby these nutrients are exchanged with other cations, often $H^+$ from the soil solution, thereby entering the soil solution and becoming available to plants.

3.3.1. Nutrient supply

Nutrient supply within the soil is directly affected by the soil acidity (Thomas, 1996). Acidity is dependent on the concentration of hydrogen ions in the soil solution and is measured as a pH value. Hydrogen and aluminium are the main cations affecting soil acidity with hydrogen ions potentially becoming toxic to plants at low pH values. Where soil pH falls to less than 5.0 aluminium, iron and manganese become soluble and may be bound by organic matter or be available for ion exchange. At these low pH values these elements may be soluble to such an extent that they may be toxic to certain plant species. Iron, manganese and zinc are less readily available to plants at alkaline pH values whereas calcium is available in greater amounts at high pH values. Phosphorus is most readily extracted at values of around pH 6.5 (Foth, 1990).

Pitty (1978) identifies the best index of potential soil fertility as the capacity of that soil to exchange cations. In temperate soils, Bohn et al. (1979) found the cation exchange capacity (CEC) to lie normally within the range 150 – 300 meq 100 g$^{-1}$ soil while Smith et al. (1987) found that, in soil-forming materials on reclaimed mine soils, the value is often less than 10% of these values.

In their recent research, Andrews et al. (1998) highlighted five factors in order to explain 48% of the variance in tree growth on restored mine soils. The first of these was the physical factor of rooting depth; but they found that the most important chemical factor limiting growth was the concentration of soluble salts, which is
estimated by obtaining a measure of electrical conductivity. Growth rates are seen to fall as electrical conductivity increases. This supports the findings of Mengel and Kirkby (1982) who showed that the concentration of soluble salts affected a range of metabolic processes including respiration, protein synthesis and the assimilation of CO₂. McFee et al. (1984) also found that electrical conductivity was the chemical property most frequently related to plant growth on reclaimed mine soils in their study areas of Indiana and Illinois. Bussler et al. (1984) showed high concentrations of soluble salts and extremes of pH to be limiting to tree growth on reclaimed mine soils. Table 3.4 shows the figures produced by Bradshaw and Chadwick (1980) (based on 1:1 and 1:2 spoil:water suspensions) indicating the effects of the concentration of soluble salts, as determined by electrical conductivity measurements (μmhos cm⁻¹), on plant species. In addition to electrical conductivity, Andrews et al. (1998) found two other chemical factors to be influential in restricting plant growth. Firstly, concentrations of extractable P were found to be important, as P deficiency is widely recognised as being limiting to growth of vegetation, and secondly, concentrations of exchangeable Mn were significant, as high levels tend towards toxicity and limited growth.

Table 3.4 The effects of soluble salts on plant species. (From Bradshaw and Chadwick, 1980.)

<table>
<thead>
<tr>
<th>Negligible effect of soluble salts: possible nutrient deficiency</th>
<th>1:1 spoil:water suspension</th>
<th>1:2 spoil:water suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μmhos cm⁻¹</td>
<td>μmhos cm⁻¹</td>
</tr>
<tr>
<td>Level for most well-fertilised spoils – salt sensitive plants may be injured</td>
<td>0.9 – 1.8</td>
<td>0.6 – 1.2</td>
</tr>
<tr>
<td>Increasing indication of high concentrations of soluble salts: possible severe growth restriction</td>
<td>1.8 – 3.6</td>
<td>1.2 – 2.4</td>
</tr>
<tr>
<td>Only tolerant species will grow satisfactorily</td>
<td>3.6 – 7.2</td>
<td>2.4 – 4.8</td>
</tr>
<tr>
<td>Injury to all species: requires long periods of leaching</td>
<td>7.2</td>
<td>4.8</td>
</tr>
</tbody>
</table>
3.3.2. Nitrogen in the soil

Nitrogen forms an essential component of chlorophyll and other plant enzymes, and is essential for plant growth and development (Bohn et al., 1979). Soil nitrogen is largely derived from nitrogen gas in the atmosphere, with micro-organisms within the soil fixing this N\(_2\) to produce organic nitrogen and contributing to the total organic matter within the soil. Decomposition of this organic material converts some soil organic nitrogen into mineral nitrogen, in the form of ammonium (NH\(_4^+\)); nitrite (NO\(_2^-\)); and nitrate (NO\(_3^-\)); which can then be taken up by plants and micro-organisms and converted into organic nitrogen. Nitrogen movement, therefore, forms a dynamic cycle within the soil which is further affected by interaction with the atmosphere, and through the addition of fertiliser and manure. Bending, Moffat and Roberts (1991) found severe nitrogen deficiency to be a principal cause of poor response of Japanese larch on restored opencast ground. Although the total N levels were similar to a range of temperate soils (Cooke, 1967), Bending et al. (1991) found it probable that a large proportion was derived from carbonaceous material of geological origin. Although utilizable mineral nitrogen can be released from these materials (Aldag and Strzyszcz, 1980), the study by Bending et al. (1991) suggested that the mineralisation of the material was of little significance for tree growth.

Johnson and Williamson (1994) and Harris et al. (1989) provided evidence that the internal core of topsoil stored during the period of mining activity often becomes intensely anaerobic, due in part to the decomposition of deeply buried vegetation and in part to a restricted diffusion of gas. Scullion (1992) noted that mineralisation of organic matter can continue under these anaerobic conditions but that nitrification is inhibited by the deficiency of oxygen. High levels of ammonium-N (NH\(_4^+\)-N), increased soil pH, a greater concentration of soluble organic matter and a reduction in active microbial biomass have all been noted at depth within stored soil mounds. When soils are reinstated, a period of rapid nitrification often results in nitrogen loss either by leaching or denitrification, this loss of nitrogen often occurring before vegetation has had time to establish.
3.3.3. Soil organic matter

Soil organic matter, although often present in relatively small amounts, greatly influences the physical and chemical processes within the soil. Brady (1990) highlights the fact that organic matter provides an energy source for soil microorganisms; can account for one third of the cation exchange capacity of topsoil; and further declares it to be the most important factor in determining the stability of soil aggregates. Organic matter content is therefore an essential contributing force to soil structure; water holding capacity; and resistance to erosion (Adams, 1973). In relation to nutrient supply, Binns (1983) research on reclaimed surface mine working, found nitrogen deficiency to be most likely in soils containing little organic matter.

Aside from the availability of plant and animal tissue to provide the source material for soil organic matter, and the influence of temperature and rainfall in assisting with organic decomposition; other factors have been found to affect the amount of organic material retained within the soil. Nichols (1984) found that soil texture influenced the amount of humic material and nitrogen present in soil, with soils high in clay and silt generally having a higher percentage of organic material than coarser textured soils. Poorly drained soils tend to have higher levels of organic matter as the rate of decay is reduced due to poor aeration (Brady, 1990).

This study of the literature led to the decision to focus this research on a number of chemical soil properties found to be of significance in limiting the establishment, or growth, of vegetation on restored sites. The analysis included soil pH; electrical conductivity; major plant nutrients (nitrate and ammonia nitrogen, phosphate, potassium, calcium and magnesium); aluminium (as it is a potentially toxic elements); and organic carbon. Details of the sampling regime employed are presented in Chapter 6.
3.4. Measurement and determination of soil properties

A range of physical and chemical soil properties have been identified as being pertinent to this research. The following sections outline the methodologies employed to measure and monitor those properties. For many of the properties to be measured, standard methods were adopted. Where a range of methods are available, details of the method employed in this research project are provided. Details of the measurements collected are presented and discussed in Chapters 6 and 7.

3.4.1. Topsoil thickness

At each sampling point where topsoil thickness was to be determined, 3 soil cores were extracted, each 10cm apart, with an open sided auger. The thickness of topsoil was measured with a metal rule with the average of the three measurements taken as being indicative of the topsoil thickness at that location.

3.4.2. Bulk density

Soil bulk density is the ratio of the mass of dry solids to the bulk volume of the soil. The bulk volume includes the volume of the solid material and of the pore space. Bulk density for any given soil is related to the texture of that soil and there is a tendency for bulk density to increase as texture becomes coarser. Organic matter is the major factor affecting bulk density, particularly in uncultivated soils (Pitty, 1978). Even in arable and grassland soils, Williams (1971) showed that 50 per cent of the variation in bulk density can be accounted for by variations in the organic content of the soil. Changes in bulk density influence permeability, drainage rate, trafficability and penetration by plant roots and burrowing animals. The coring method for the determination of bulk density has been used for many years although, in soils where stones abound, or, if the surface soil is too loose to facilitate coring, then excavation methods can be used. More detailed explanations of the methods for extraction of a soil sample and measurement of the bulk density can be found in Rowell (1994) and Blake & Hartge (1986).
This research employed a coring method whereby a cylindrical metal sampler of known dimensions was driven into the soil to the required depth and the sample carefully removed to preserve a known volume of soil. Samples collected in the field were transported inside the sampling cylinders and once in the laboratory were carefully extruded from the corer, measured, oven dried overnight at 105°C until a constant weight was reached, and then weighed. The bulk density is then calculated by dividing the mass of the oven dried soil by the volume that it occupied in the core cylinder.

3.4.3. Particle size distribution

Particle size analysis is a measure of the size distribution of the individual particles in a soil sample. Various classification systems have been developed for soil particle size analysis, one of the most widely used being that developed by the United States Department of Agriculture (the USDA system). Under this classification system, soil particles can vary in size from cobbles (in excess of 80 mm in size), through gravel (in excess of 2 mm in size), down to sub-micron clays (of < 1 μm). As soil rarely consists of one class of particles, soil texture is based on different combinations of the sand, silt and clay fractions.

In order to enhance separation and dispersion of aggregates, pre-treatment of samples is key when undertaking particle size analysis. Removal of organic matter is often the first step in the chemical pre-treatment of many soils. Hydrogen peroxide has been recommended as the standard oxidant for most soils (Day, 1965). Soil samples must then be dispersed using a variety of chemical or physical methods. Many researchers have found that a combination of chemical and physical (such as the use of ultrasonics) provides the most complete and stable dispersion (Maeda et al., 1977; Mikhail and Briner, 1978).
Although sieving of soil samples allows differentiation of particles within the 2000 to 63 μm range there are some limitations which have been noted. Particle shape and sieve openings affect the probability of passage for example a particle whose shape will only permit passage in one orientation has a limited chance of getting through the sieve, except after prolonged shaking. The unequal size of sieve openings also mean that prolonged shaking is required if all particles are to have an opportunity of achieving passage through the largest openings (Day, 1965).

The use of sedimentation for particle size analysis relies on the relationship between settling velocity and particle diameter. The relationship, first developed by Stokes (1851) and now known as Stokes' Law is the basis of many commonly used techniques for particle size analysis including pipette and hydrometer methods (as detailed by Gee and Bauder, 1986) and X-ray/sedimentation methods as employed in this research. The SediGraph (Micromeritics® Sedigraph 5100) uses both particle falling rates and the amount of absorption of a collimated X-ray beam for particle size analysis. Particle falling rates (according to Stokes' Law) are used to determine the points in the analysis cell beyond which certain size particles have fallen, while X-ray absorption is used to determine the percentage of total particle mass at different points within the cell. The Water Resources Division (WRD) of the United States Department of Agriculture recognised the use of the SediGraph as providing a faster, and cheaper, method of size analysis and recommended it as an alternative to visual-accumulation tube, pipette, bottom withdrawal tube, or hydrometer methods of particle size analysis. It was noted that, for sizes in the silt-clay range, the SediGraph tended to indicate 5-10 percent more material being finer than the results indicated by the pipette method (WRD, 1993). If comparisons are to be made between particle size data from a range of research projects such methodological differences need to be taken into account.
3.4.4. Atterberg limits

The Atterberg shrinkage, plastic and liquid limits (developed in 1911 by A. Atterberg, a Swedish soil scientist) define differing states of mechanical behaviour within a soil and give a means of scaling water content against mechanical behaviour. To determine the liquid and plastic limits it is necessary to calculate the moisture contents which define the boundaries between material consistency states. The liquid limit defines the boundary between plastic and viscous fluid states and was determined using a standard "Liquid Limit Device," which drops a shallow cupful of soil from a consistent height of 1 cm. The number of drops required to close a 6 mm groove cut through the sample is recorded and a moisture content sample processed. The plastic limit defines the boundary between non-plastic and plastic states and was determined simply by rolling a thread of soil and adjusting the moisture content until the thread breaks at a diameter of 3 mm.

Greater amounts of organic matter within a soil tend to increase the plastic and liquid limits, probably due to the fact that they reduce compaction and that there is a strong attraction of water to humic material (Pitty, 1978). There is a trend that as the liquid limit increases then soil compressibility increases, also as the plasticity index increases the shear strength of the soil decreases.

3.4.5. Shear strength

Soil will deform under stress with the mechanical strength of a soil being described as the shear strength at the point of failure. A hand shear vane tester can be used for field measurement. This comprises a torque head with a direct reading scale, which is turned by hand at a consistent speed until shearing occurs at which stage a non-return pointer on the head provides a reading. Testers are supplied with vanes of differing diameters. For this research, the tester used was a Pilcon Hand Shear Vane which was supplied with two vanes: one of 19 mm diameter/28 mm blade length and one of 33 mm
diameter/50 mm blade length. The 19 mm diameter vane can be used to measure 0-120 kPa of shear strength, while the 33 mm diameter vane registers from 0-28 kPa of shear strength. Here, the shear vane was forced into the soil, with minimal sideways movement, to a depth of approximately 60 mm. Values of shear strength were recorded in kPa.

3.4.6. Volumetric soil moisture

Data for the collection of the surface soil moisture content can be obtained using a ThetaProbe soil moisture sensor developed by the Macaulay Land Use Research Institute and manufactured by Delta-T devices. The ThetaProbe is designed to match other methods, such as time-domain reflectometry or capacitance measurement, but using a less complex and expensive collection procedure. Validation against other methods of determination of soil water content have shown agreement of around ±0.02 m³ m⁻³ (Miller & Gaskin, 1998).

Volumetric soil moisture, \( \theta_v \), is the ratio between the volume of water present in the soil and the total volume of the sample. A dimensionless parameter, it can be expressed as either a percentage (% volume), or as a ratio (m³ m⁻³) where an oven-dry soil corresponds to 0 m³ m⁻³ and water gives a reading of 1.0 m³ m⁻³. Field measurements of a wet mineral soil could approach 0.5 m³ m⁻³ while a wet organic soil could approach 0.8 m³ m⁻³. The ThetaProbe measures volumetric soil water by responding to changes in the apparent dielectric constant. The instrument converts the signal into a direct current (DC) voltage shown to be almost proportional to the soil moisture content. The probe, shown in Figure 3.1, comprises four sharpened prongs of 6 cm in length. An estimate is obtained for a 30 cm³ cylinder of soil within these prongs. A comprehensive description of the operating principles of the probe are given by Gaskin and Miller (1996). The impedance of the emitted 100 MHz signal is influenced by two properties; the apparent dielectric constant and the ionic conductivity. The signal frequency minimises the effect of changes in the ionic conductivity to maximise the sensitivity of the signal to changes in the dielectric
constant. The reported absolute accuracy of the probe is given as between \( \pm 0.02 \) and \( \pm 0.05 \text{ m}^3\text{ m}^{-3} \) depending on whether a soil specific calibration is used or the supplied generalised calibration parameters are used. The output voltage readings (V) are recorded on a digital voltmeter.

![Figure 3.1 ThetaProbe for determining volumetric soil moisture](image)

In the early stages of this research, a set of 18 soil samples were collected across the study site to support a preliminary soil analysis. An estimate of organic matter was obtained by means of loss on ignition, for 16 hours at 360°C (Storer, 1984), and showed values for the topsoil horizon (0-20 cm) ranging from 5.7% to 14.6% with a mean of 9.0% and a standard error of 0.7. The USDA soils classification categorises all soils with 10% (or less) organic materials as mineral soils. The mean value for loss on ignition for the samples analysed was lower than this threshold, and the standard error was low, so for the purposes of this research, the generalised calibration for mineral soils for the ThetaProbe was used for the collection of all soil moisture data. This introduces the potential for error of \( \pm 0.05 \text{ m}^3\text{ m}^{-3} \) for individual samples but, given
that a minimum of 60 readings would be averaged to give an indicative value for each sample point, it was felt that this potential error would be compensated by allowing for, and measuring, the natural variability of volumetric soil moisture at each sample point.

3.4.7. Soil pH

The two main methods for determining pH are colorimetric and electrometric. Colorimetric methods are based on weak acids or weak bases whose colours change with undissociated or dissociated forms. Electrometric measurements are more common, in the vast majority of cases being determined using a glass electrode-calomel system. For the purposes of this research a glass electrode-calomel system was employed. Two buffer standards were used (pH 7 and pH 4). The pH was determined using a 2:1 solution of de-ionised water and soil, which was well mixed, and allowed to stand for 10 minutes prior to readings being taken. Electrodes were rinsed with distilled water between readings.

3.4.8. Electrical conductivity

Electrical conductivity (EC) provides a means of assessing the level of soluble salts within a soil. The concept behind EC is that the electrical current carried by a salt solution will increase as the salt concentration of the solution increases. To determine EC an electrical potential is applied across two electrodes of known geometry which have been placed in a sample solution. The resistance \( R \) of the solution between the electrodes is measured in ohms (Bresler et al., 1982). Specific resistance \( R_s \) is the resistance of a sample of volume 1 cm\(^3\) but, as most conductivity cells work on smaller volumes of sample, only a fraction of \( R_s \) is measured, this fraction being the cell constant \( K = R / R_s \). The reciprocal of the resistance is conductance \( C \) which is expressed in reciprocal ohms or mhos. The reciprocal of \( R_s \), the specific conductance, is the electrical conductivity (Rhoades, 1993) and is expressed in micromhos per centimetre (\( \mu \text{mho cm}^{-1} \)), millimhos per centimetre (\( \text{mmho cm}^{-1} \)) or, in SI units, as microsiemens per centimeter (\( \mu \text{S cm}^{-1} \)).
For this research, a saturated paste of each soil sample was prepared by mixing a 10 ml scoop of air-dry soil with 50 ml of de-ionised water. After mixing thoroughly, the sample was allowed to sit for several hours to allow the readily soluble salts to dissolve. An extract of this saturated paste was then filtered off and the EC measured using an appropriate conductance meter (following the procedure described by Sparks, 1995).

Many factors have been found to affect soil EC variability in the field (Hartsock et al., 2000), including those which influence the amount and connectivity of soil water (bulk density, structure, water potential, precipitation and the timing of the measurement); soil aggregation (proportions of cementing agents such as clay and organic matter); electrolytes in the soil water (salts and exchangeable ions); and the conductivity of the mineral phase (the types and quantities of minerals and exchangeable ions). Bulk soil EC measurements have been related to a range of individual factors including salinity (Rhoades and Corwin, 1981), clay content at 15 m depth (Williams and Hoey, 1987) and soil moisture content (Kachanoski et al., 1988). The relation between EC and other soil properties measured as part of this research are discussed in Chapter 7.

3.4.9. Plant nutrients

Standard methods and procedures employed by the Department for Environment, Food and Rural Affairs (defra, formerly MAFF) can be found in their manual of analytical methods (HMSO, 1986). These precise laboratory methods for chemical analysis of soil properties, while yielding useful data, can be expensive and time consuming. Simpler methods of field (or laboratory) testing have a useful role to play in practical soil management, as results can be obtained quickly and at a minimum cost. One such field-based alternative is the Palintest Photometer and Soil Test System (Palintest Ltd., Gatehead, England). Soil analysis is carried out by extracting nutrients or trace elements from the soil and then testing the extracts using colorimetric test procedures.
Chemical elements may be strongly bonded within the soil structure and soil analysis will measure only those nutrients or trace elements which are exchangeable or extractable under the conditions of the test. The amounts measured will depend upon the extraction method used. A general relationship exists between different methods of soil analysis although precise correlation between methods is not always possible. In a comparison between the Palintest methods and the standard methods employed by ADAS, Marks and Argent (1989) found good correlation between the two methodologies.

Figure 3.2 Correlation between Palintest and standard ADAS methods, (data from Marks and Argent, 1989)
Based on the data provided, Figure 3.2 shows the correlation graphs for nitrate-N, phosphate-P, potassium and magnesium. The comparative analyses were carried out on samples for a range of typical agricultural and horticultural soils and indicate that the Palintest system offers a useful and convenient method of soil chemical analysis. The Palintest system was used in this research to provide details of nitrate and ammonia nitrogen, phosphate, potassium, calcium, magnesium and aluminium.

3.4.10. Organic carbon

Carbon is the main element present in soil organic matter, comprising between 48 - 58% of the total weight (Nelson and Sommers, 1996). Organic C has often used as the basis for an estimate of organic matter through multiplying the organic C value by a factor. The widely used Van Bemmelen factor of 1.724 assumes that organic matter contains 58% organic C. Studies have shown that the proportion of organic C in soil organic matter is highly variable and that no factor exists which would be appropriate for all soils (Broadbent, 1953). These findings would suggest that it is more appropriate to determine and report the organic C in a soil rather than to use an approximate conversion factor in order to report the organic matter content.

Organic C may be determined by any of three methods. Firstly, by determining total C and inorganic C and subtracting the inorganic portion from the total C value; secondly, by determining the total C of a sample after destruction of the inorganic C; and thirdly, by the oxidation of organic C compounds by $\text{Cr}_2\text{O}_7^{2-}$ and subsequent determination of the unreduced $\text{Cr}_2\text{O}_7^{2-}$ by oxidation-reduction titration with $\text{Fe}^{2+}$ or by colorimetric methods. Of these methods, the oxidation by $\text{Cr}_2\text{O}_7^{2-}$ is the most rapid and simple, and requires no special equipment. The Walkley and Black method (1934) oxidises organic C through the heat given off by dilution with $\text{H}_2\text{SO}_4$. Although the results obtained cannot be considered quantitative it is a simple, rapid, and widely used method which gives an approximate organic C concentration. Details of the procedure can be found in Nelson and Sommers (1996). This latter method (based on Walkley and Black,
1934) was employed in this research to give a determination of the organic carbon of the soil samples collected.

3.5. Tree species variation

In addition to measuring and monitoring the soil properties across the study site, it was also necessary to take note of patterns of vegetation across the area. Newbould (1989) identified a growing environmental awareness and public concern over the loss of mature hedgerows and other wildlife habitats. This in turn has led to increasing moves toward restoration of land which provides habitats for native species. Native trees play an important part in any restoration process for the provision of food and shelter for a range of insects, birds and mammals. Bending et al. (1999) recognised that, where natural soils were available for restoration, the attempt to cultivate native species may be justified but, in areas where soil-forming materials were to be used, difficulties may arise. Restoration and aftercare plans presented at the time of the planning application must include details of proposed planting schemes which will often include the planting of suitable indigenous species where possible. The nature of restored soils poses a number of potential problems for the successful cultivation of a range of native species.

Scullion and Malinovszky (1995) showed that common alder (*Alnus glutinosa*) grows well on restored opencast sites in comparison with other tree species. This supports the findings of Voysey (1961) in relation to restored opencast soils and Moffat et al. (1989) in relation to spoils. Alder is recognised as being productive on disturbed land in general because of its ability to fix atmospheric nitrogen. A comparison between sites led Scullion and Malinovszky (1995) to indicate less growth in shallower soils, and where total pore space and organic content were lower. In recent years, there has been an awareness that, despite impressive early growth, the species is prone to die-back. There is an implication that the water holding capacity of most restored soils is inadequate for all but juvenile alder trees.
Research by Bending et al. (1991) into the success of Japanese larch (*Larix leptolepis*) on colliery spoil found that the increased moisture requirements of mature trees often exceeded that available from the soil leading to an increased occurrence of surface soil drought conditions. Studies by Moffat and Roberts (1988), Bending et al. (1991) and Moffat et al. (1989) showed that many tree species performed poorly on soils subject to prolonged waterlogging. Birch (*Betula spp.*) has been found, by Frivold and Mielikainen (1991) and Scullion and Malinovszky (1995), to be particularly sensitive to site conditions and to respond poorly on wetlands and soils with a poor supply of O$_2$. Binns (1983) found oak (*Quercus spp.*) to be tolerant of wet soils although it has been found to grow slowly in the early years. Moffat (1990) indicated that certain conditions associated with newly restored opencast land, in particular the low organic content, are unlikely to be suitable for *Quercus* species. Scullion and Malinovszky (1995) found that total pore space and organic content were important contributing factors, while high levels of extractable magnesium was an important limiting factor, in influencing growth of this species.

Among the figures published by Bradshaw and Chadwick (1980) are those shown in Table 3.5 which give acceptable pH ranges and soil compaction levels for a variety of tree species.

<table>
<thead>
<tr>
<th>Species</th>
<th>pH range</th>
<th>Level of Compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Alnus glutinosa</em></td>
<td>3.5 - 7.5</td>
<td>compacted</td>
</tr>
<tr>
<td><em>Quercus spp.</em></td>
<td>4.0 - 7.5</td>
<td>loose</td>
</tr>
<tr>
<td><em>Pinus spp.</em></td>
<td>3.5 - 8.0</td>
<td>loose</td>
</tr>
<tr>
<td><em>Fraxinus spp.</em></td>
<td>4.5 - 8.0</td>
<td>loose or compacted</td>
</tr>
</tbody>
</table>

A discussion of these findings in relation to the conditions found at the study area for this research project form part of Chapters 6 and 7.
3.6. Summary

Research to date has shown that the limitations imposed by many of the factors which constrain vegetation growth in natural soils are amplified in situations where soils are restored. The factors affecting successful restoration of land after opencast mining fall broadly into two categories. Firstly, there are those factors affecting the water content of the soil and the supply of that water to the vegetation and, secondly, there are the range of soil properties which either assist or restrict vegetation growth. These factors are important in natural soil and plant relationships but are of special interest in manmade environments where the processes and procedures employed to create the artificial landscape can have a direct and significant impact on the success of the plant restoration.

Shallow replaced soils can restrict plant rooting depth. Handling and storage of soil during opencast mining operations can lead to a loss of soil structure which causes increased compaction, reduced porosity, restricted rooting depths, a tendency to waterlogging and the development of anaerobic conditions. The nutrient balance of soil can change, in particular with regard to nitrogen supply, with leaching and denitrification being common in the period immediately after restoration.

Often, planting regimes are developed and implemented at a site level with little importance afforded to in-site variations in soil properties. This thesis contests that the monitoring and analysis of readily obtainable data, describing a range of soil parameters across a site, could lead to useful information for planning and restoration of sites to woodland.
Chapter 4. GIS methods for environmental planning

"Computers are useless. They can only give you answers." Pablo Picasso (1881-1973)

4.1. Introduction

To describe geographical phenomena it is necessary to determine both what is present, and where it is located (Burrough and McDonnell, 1998). Conceptual models of space are fundamental to the fields of human geography, where social interactions are played out in some form of spatial arena, and to physical geography, where patterns and processes are explored and explained in terms of variation over space and time. Fischer et al. (1996) highlight several reasons for the use of a spatial perspective in data analysis. Space provides a simple, but useful, framework into which large amounts of data can be set. A spatial perspective provides access to additional information on the relative location of objects or events and facilitates the linking of these objects and events. More pertinent to the subject of this research however, is the observation that, for environmental (and social) applications, the distance between objects and events may often play an important role in determining any interaction between them. This concept of spatial autocorrelation where 'everything is related to everything else, but near things are more related than distant things' (Tobler, 1970), forms the basis of much spatial analysis. Given an appropriate data model and suitable algorithms within the modelling software, the researcher has a means to predict values of a given attribute at unsampled locations based on known values of that attribute at sampled locations. The use of GIS provides a range of data models (both vector and raster based) and a variety of analytical tools and modelling algorithms. As empirical data collection is often time-consuming and costly, the use of GIS as a means of capitalising on data collected in the field provides a useful addition to the researchers tool kit.
4.1.1. Geographical information systems

Many definitions of Geographic Information Systems (GIS) exist in the literature (Burrough, 1986; DoE, 1987; Cowen, 1988; Aronoff, 1989). Using a mathematical analogy, a GIS allows a series of operations similar to those found in traditional statistics and algebra, the difference being that the variables being processed by the GIS are entire maps. Working from the premise that the main function of a computer-based GIS is to facilitate the storage, manipulation and processing of spatial data, it is possible to view the data structure conceptually as a series of 'floating maps'. The existence of a common geographical reference system allows the user to interrogate and manipulate any combinations of these map layers (see Figure 4.1). The main difference in working with these digital map layers as opposed to working with traditional analogue paper map sheets, is that the digital spatial data are stored numerically and therefore allow for quantitative (as well as qualitative) processing.

Geographical information systems have the ability to store and manipulate spatial data. The underpinning database systems must provide core functionality for storing, retrieving and updating spatial and attribute information but the real power of the GIS is in the additional functionality. Most commercial GIS comprise a selection of statistical and analytical tools which facilitate spatial modelling and it is these tools which distinguish the GIS from other information or map production systems. Among the required functionality of a GIS, Worboys (1995) includes the ability to create and maintain resource inventories; to carry out network analysis; to undertake terrain analysis; to perform analysis on multiple layers of data; to undertake locational analysis; and to manipulate data from multiple sampling epochs. It is clear, therefore, that GIS technology provides a useful tool for a broad range of research applications. Research projects can benefit in many ways: from having the ability to store and combine data from diverse sources into a common spatial reference system; through having access to functionality that allows new data to be derived or modelled from existing data; by having the capacity to explore and analyse data; and by having the means to output data and results in a range of explanatory formats. The field of environmental modelling is one of many that can benefit from the use of these tools.
4.1.2. Environmental planning

Many human activities, including large scale industry, construction and agriculture have a considerable impact on the natural environment. It is the growing concern regarding these impacts and their consequences in both the short and long term that have led to environmental issues becoming of increasing global importance. Concern for the environment ranges from the local scale where individuals seek to understand the implications of actions about what happens in the area immediately surrounding their homes, to the global scale where national leaders get together to discuss issues transcending international borders. GIS are finding an increasing number of applications in environmental planning from site design covering small areas to the development of regional strategies. A timely coincidence was that, as this chapter was being written, international leaders were gathered in Johannesburg, South Africa for the 2002 Earth Summit where discussions covered such issues as water supply, ecosystem preservation, corporate accountability and renewable energy resources. Gilfoyle (1991) notes among the advantages offered by GIS the rapid and easy access to large volumes of data which can be easily amended and updated; the ability to select
information by area or by theme; the ability to merge data sets; the ability to search for particular features or conditions and the ability to undertake simulation or modelling tasks.

Most environmental problems have an obvious spatial dimension and consequently environmental modelling has always required the use of spatial information, although procedures for integrating this information with the modelling process have been limited as traditional statistical approaches constrain the spatial variability within the data (Berry, 1993). GIS affords the opportunity to produce much more than just cartographic output from the data under investigation. The facility to reclassify data, overlay map layers, derive new variables from one or more existing map layers, measure distances, proximity and connectivity all mean that, in the field of environmental modelling, complex systems can be addressed in a new way and that the mapped data becomes real spatial information. As Berry (1993) points out, the dominant feature of GIS technology is that spatial information is represented numerically, as opposed to in an analogue format as was the case with printed map sheets. This opens up the potential for quantitative, as well as qualitative, analysis of the spatial information. Developments in the field of spatial statistics have sought ways to characterise the geographical patterns of mapped attributes (in contrast to traditional statistics which often assume uniformity over space).

The increasing use of GIS as a tool for research affords many examples within the literature. Looking solely within the sphere of environmental modelling: resource inventories such as regional land cover databases have been developed (the NLCD\textsuperscript{1} in the United States; the CORINE\textsuperscript{2} database produced by the European Environment Agency; the Africover project sponsored by the Food and Agricultural Organisation of the United Nations). Network analysis routines can be used for flood prediction (Muzik, 1996) and to model water chemistry (Smart \textit{et al.}, 2001).

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Algorithms for terrain analysis support models of surface runoff (Frankenberger et al., 1999), landslide hazards (Lan et al., 2003) and soil erosion (Jain and Kothyari, 2000). Multi-layer analysis provides support to habitat and biodiversity modelling research (Azevedo et al., 2000, Wadsworth & Treweek, 1999). Locational analysis routines are used within a range of research from identification of landfill sites (Basagaoglu et al., 1997) to habitat identification (Pereira and Itami, 1991). The ease with which data can be stored and manipulated within a GIS offers benefit to research having a temporal, as well as a spatial dimension. GIS are often used in areas such as the analysis of landuse change over time, deforestation being an obvious example (Skole and Tucker, 1993); the spread of disease (Rushton et al., 2000); or the dispersal of particular animal species (Macdonald & Rushton, 2003). This cited research provides just a small indication of the broad range of environmental research areas in which GIS are proving a useful tool. The development of environmental models is not an end in itself. Rather, these models should provide information which in turn is used to inform policy and legislation. The ultimate aim is to ensure that, where decisions have to be taken which will have a negative impact on the environment (such as the siting of an opencast coal mine), that the impact will be as small as possible. Conversely, where decisions are taken regarding amelioration of environmental conditions, that the environmental benefit will be maximised.

4.1.3. From modelling to policy

Developments in the field of environmental modelling help with an understanding of earth surface processes but become of increasing value if they can help to inform policy development and decision making. Better information leads to better decisions and it may be that environmental models can be used to increase public education or involvement in decision making processes; or that the output from the models can be used for risk assessment and risk management. Models may be used in the planning process by providing information to assist in the siting of new facilities or to assess the impact of expansion of existing operations. Many decision-makers may lack the time or the technical background required to process large amounts of information or to undertake detailed analysis. Couple these limitations with the fact that much scientific
research provides results in formats which are inaccessible to non-expert audiences, and it is obvious that much potentially useful information is not being translated into useful policy-forming information. Busby (2002) highlights the need for information to be made useful and usable and identifies organisational challenges that must be tackled in order for the scientific and policy-making communities to integrate more fully.

4.2. Data collection issues

Having determined that GIS provides a means whereby empirical data can be stored, organised and analysed to support a range of environmental research applications, it falls next to the researcher to determine the methods by which pertinent data can be collected and verified.

Data collection issues arise regardless of the nature of the research being undertaken, and whether or not that data also has a spatial dimension. Decisions must be taken regarding sampling density, sampling frequency and sampling locations. Available statistical techniques must be investigated in order to ensure that suitable methods are employed to explore the collected data and to present any findings in an applicable manner. When seeking to build a spatial digital database there are additional issues which must be considered and, when using a GIS as a tool for data manipulation, a new set of spatial analytical techniques must also be explored and assessed. This section seeks to explore some of the issues related to the collection of data in the field; the subsequent digitisation of that data and some factors to be considered when the spatial dimension of the data is as important as the measured attribute.

4.2.1. Sampling

The environment is continuous but often time and cost constraints mean that properties can only be measured at a finite number of places. Where sampling does not occur, estimates or predictions can be made from the sampled data using a range of
interpolation algorithms. The purpose of sampling is, therefore, to estimate values for the parameters of interest with an accuracy acceptable to the task in hand and at the lowest possible cost (Petersen and Calvin, 1986). If the population from which the sample is being drawn is relatively homogeneous, then a small sample might provide adequate information. This research is largely focused on a range of soil parameters and, with soil, as with many other natural phenomena, heterogeneity is more usually the rule. Soils often show a great deal of variation in their measured properties (Davidson, 1992), often across relatively small distances (Beckett and Webster, 1971), therefore the location of sample points can be critical for subsequent analysis. Regular sampling provides the best coverage for mapping but can lead to a bias in results if the sampling network corresponds to some form of regular pattern in the landscape (for example a regular system of drainage ditches). Random sampling is favoured for the determination of unbiased means and variances (Petersen and Calvin, 1986) but has drawbacks in the field as each point needs to be located separately (as compared to the use of a regular grid where the origin can be located and fixed with additional points being determined as offsets from that origin). Unless a large number of samples is to be taken, a completely random sampling strategy can lead to an uneven distribution of points across an area. Compromises include the use of stratified random sampling where regular areas are delimited and then individual sampling locations selected at random within each area. Other options include clustered, or nested, sampling which allows for the exploration of spatial variation at different scales; and transect sampling to survey profiles of rivers, hillsides or beaches. Figure 4.2. shows examples of these sampling strategies for collecting data from point locations.

Alongside the determination of the sampling strategy to be employed, decisions must also be taken regarding the appropriate number of samples to adequately describe the property under investigation. Any survey involving the collection of data to describe a heterogeneous material, such a soil, must take into account the methodological problem of determining a sampling strategy to adequately describe the spatial variability of that soil. Various approaches have been suggested by researchers. Steur (1961) suggested a range from 16 observations per hectare for a 1:5,000 scale soil
survey to 6 observations per hectare for a 1:50,000 scale survey. Dent and Young (1981) suggest 2 observations per hectare for a 1:5,000 scale soil survey to 1 observation per 13.5 km² for a 1:250,000 scale.

Ameyan (1986) is critical of this approach as there is the presumption that the same degree of variability occurs over the entire area under study which can lead to a loss of important information through under-sampling or wasted efforts if large amounts of unnecessary data are amassed. Wilding and Drees (1983) determined that, for temperate environments, by taking 15-25 samples the mean of some soil properties could be estimated to ± 10% while for others the precision was only ± 25%. Similarly Warrick and Neilson (1980) found that 2 samples for bulk density but 1300 samples for hydraulic conductivity were required to estimate the mean within 10% at the 0.05 significance level. Ameyan (1986) found high levels of variability of many soil parameters within each of his 200 m² test plots with pH showing the lowest level of
variability across the sites while cation exchange capacity, exchangeable calcium and magnesium showed the greatest variability. It would seem therefore that no absolute guidelines exist for the sampling of soil properties and any interpretation of results must bear in mind the potential spatial variability of measured parameters.

In this research a stratified random sampling technique was employed where three regions of interest were selected, based on topographical features and vegetation success rates. Within these three regions a set of sampling points was selected on a random basis. Once these sample points had been identified and marked on site, data were collected regularly for topsoil volumetric moisture content and topsoil shear strength. To give a representative indication of these attributes, measurements were taken along a five metre transect extending from the sample point, the measurements being averaged to give a recorded value for that point. Topsoil thickness, topsoil bulk density and topsoil volumetric soil moisture data were also collected across each of the three regions of interest using a random sampling technique. These sampled data were then used to predict values across each of the three regions. Details of the sampling regime, frequency of sampling and determination of mean values for each sample point are given in Chapter 6.

4.2.2. Building a digital database

It is widely recognised that building an accurate GIS database is an exacting and time-consuming task (Burrough and McDonnell, 1998). Raw data may be available in many different analogue and digital forms: as printed maps or photographs; as satellite data; or as published tables of information. In order for features on the earth's surface (effectively a spheroid) to be represented on a flat surface map, some form of map projection must be employed, but all map projections will distort shape, area, distance or direction to some extent and the combining of source data from different projections often leads to positional error being introduced into digital data. When obtaining digital data from third parties, consideration must be given to the original purpose of those data and whether the scale at which the data was collected is appropriate to the
task to which it is to be applied. There are three possible ways of pooling data sources into a digital database: either by purchasing data in a digital form from a supplier; by digitising existing analogue data; or by carrying out a new digital survey to obtain the required information. Regardless of the source of the data, it must all be referenced to a common coordinate system: this common geographical 'space' providing the arena in which data from the various sources can be combined and analysed. The most usual coordinate system used in GIS is that of plane, orthogonal Cartesian coordinates which by convention are oriented north-south and east-west with elevations referenced to mean annual sea level.

Some of the data for this research project were supplied from a commercial supplier (the aerial photography), some involved digitisation of existing analogue sources (maps and plans of the site obtained from the original planning application), and some were obtained from field survey (the topographic survey which included elevation data, lakes and drainage channels). One of the primary tasks when setting up the digital database for use with the GIS software was to ensure a common coordinate base for each of these sets of data. One element of the research was focused on soil moisture patterns. It was recognised from an early stage in the project that a model of the slope of the ground would be required to help with the exploration and explanation of soil water movement across the site. In order for the GIS software to determine slope, the digital data needed to be in a metric coordinate system and not in geographical degrees of latitude and longitude. As the study site covered a small geographical area the decision was taken to use the British National Grid (a metric coordinate system) as the basis for all digital data layers.

Aerial photographs of the study site were obtained but had not been geographically referenced. A series of ground control points were identified (both on the aerial photographs and in the field using a GPS) with these points being referenced to British National Grid coordinates. Once the aerial photographs had been geographically
rectified using these control points, additional processing was able to draw out useful information on tree density values across the site.

Elevation data were obtained by means of a topographic survey undertaken using a Leica total survey station with control points again registered to British National Grid coordinates using differential GPS positioning. This series of point elevation data was subsequently used to determine layers of elevation, slope and aspect for the entire study site using methods described in §4.3 below. The locational information for the sample points used by subsequent field surveys of a range of soil parameters was provided from a hand-held GPS and the data used to generate layers of topsoil depth and topsoil bulk density and topsoil moisture conditions using geostatistical methods described in §4.5 below. Additional information detailing areas of mineral extraction and restoration timings was obtained from printed analogue maps of the area which accompanied the planning application. These details were digitised and geographically referenced using control points obtained from the grids printed as part of the analogue product. Additional information regarding these various data sources and their use within the research project can be found in Chapters 5 and 6.

4.3. Generation of terrain models

As gridded surfaces are supposed to be mathematically continuous it is, in theory, possible to derive a mathematical value for any point in space. In practice, these values are approximated either by computing the differences within a square filter or by fitting a polynomial to the data within the filter. When dealing with elevation data the two first order derivatives are the slope and the aspect of the surface, with second order derivatives being the profile and plan curvature (Evans, 1980). Gradient (or slope) is usually measured in degrees, per cent or radians; aspect in degrees, usually converted to a compass bearing; and curvature in degrees per unit of distance (e.g. degrees per 100m). A variety of methods are available for the computation of slope and aspect. Burrough and McDonnell (1998) report that, of eight algorithms for computing slope and aspect, and compared using RMS residual error values derived from the difference
between values generated by the algorithm and true values for test surfaces, the second-order finite difference method fitted to the four closest neighbours in the window (Zevenbergen and Thorne, 1987) is best for smooth surfaces.

This method determines slope by

\[
\tan \text{Slope} = \left[ \left( \frac{\Delta z}{\Delta x} \right)^2 + \left( \frac{\Delta z}{\Delta y} \right)^2 \right]^{0.5}
\]

where \( z \) is altitude and \( x \) and \( y \) are the coordinate axes.

Aspect is given by

\[
\tan \text{Aspect} = -\left( \frac{\Delta z/\Delta y}{\Delta z/\Delta x} \right).
\]

Using this approach, analysis is based on a rectangular matrix of evenly spaced elevations covering the area of interest. A 3x3 submatrix is analysed repetitively across the altitude matrix. The calculated indices relate to the central point of the submatrix. To represent the land surface accurately it is necessary that the surface generated by an equation passes exactly through all the nine of the submatrix elevations. This type of surface is produced by the partial quadratic equation:

\[
Z = Ax^2y^2 + Bx^2y^2 + Cx^2y^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I
\]

The relationship between these parameters (A to I), the 9-cell submatrix, and the topographic indices is shown in Figure 4.3. Given the smooth nature of the topography at the study site for this research project, this method was used to determine slope and aspect derivatives from the surveyed elevation data. Further details, and maps of these derived grids, are presented in Chapter 6.
\[ A = \frac{(Z_1 + Z_3 + Z_7 + Z_9) \cdot 4 - (Z_2 + Z_4 + Z_6 + Z_8) \cdot 2 + Z_5 \cdot 4}{4} \]
\[ B = \frac{(Z_1 + Z_3 + Z_7 + Z_9) \cdot 4 - (Z_2 + Z_8) \cdot 2}{2} \cdot 4 \]
\[ C = \frac{(Z_1 + Z_3 - Z_7 - Z_9) \cdot 4 - (Z_2 - Z_8) \cdot 2}{2} \cdot 4 \]
\[ D = \frac{(Z_4 + Z_6) \cdot 2 - Z_5}{2} \cdot 4 \]
\[ E = \frac{(Z_2 + Z_8) \cdot 2 - Z_5}{2} \cdot 4 \]
\[ F = \frac{(-Z_1 + Z_3 + Z_7 - Z_9) \cdot 4}{4} \cdot 4 \]
\[ G = \frac{(-Z_4 + Z_6) \cdot 2}{2} \cdot 4 \]
\[ H = \frac{(Z_2 - Z_8)}{2} \]
\[ I = Z_5 \]

SLOPE = \sqrt{G^2 + H^2}
ASPECT = \arctan(-H/-G)

Profile curvature

PrC = \frac{2(DG^2 + EH^2 + FGH)}{(G^2 + H^2)}

Plan curvature

Pnc = \frac{-2(DH^2 + EG^2 - FGH)}{(G^2 + H^2)}

concave = positive
convex = negative

Figure 4.3 Computing slopes using Zevenbergen and Thorne's (1987) method.
4.4. Aerial photographs and vegetation cover

Vegetation mapping has been assisted for many years by the visual interpretation of aerial photographs. Homogenous patches could be delineated and properties attached describing the vegetation species, height, density and under-storey cover. Some of these properties can be determined using photogrammetric methods, for example Lillesand and Kiefer (2000) describe the determination of vegetation height measurements using a parallax bar; while other properties can be inferred from the tone, colour, shape, texture, pattern and context observed in the aerial photograph (Estes et al., 1983).

The use of satellite imagery has dominated vegetation mapping in recent years with use of data from the visible, near-infrared and mid-infrared wavelengths of the solar spectrum. Digital analysis of satellite imagery cannot match the quality of vegetation maps derived from high quality interpretation of air photographs (Woodcock et al., 2002) and air photographs continue to remain an important source of data especially in studies where costs are restrictive or where a greater level of spatial detail is needed than can be achieved with satellite imagery.

Within this research project an attempt was made to determine the extent to which information on tree density, derived from the aerial photographs, agreed with field observations. The method employed, and the findings are presented in Chapter 7.

4.5. Interpolation

Interpolation is an important feature of any GIS as data are sampled at discrete locations and so geographically referenced data are often fragmentary. Often the need arises to be able to predict or infer values for locations where no sampling has taken place.
Because the data are sampled at point locations any interpolated map is always an approximation. Burrough (1993) identifies measurement errors and short range variation as contributing to, an often very large, local uncertainty. The method used for interpolation will also contribute to uncertainty in the predicted values. Interpolation errors may be systematic, resulting from the use of an inappropriate method; or they may be unbiased but essentially unknown, because the interpolation method assumes a smooth, continuous spatial variation following a standard spatial model (Burrough, 1986). A range of interpolation methods are now provided as standard tools within many GIS, the most common being nearest neighbour, inverse distance weighting (IDW), splines and, more recently, geostatistical (or Kriging) methods.

4.5.1. Linear interpolation methods

*Nearest Neighbour* interpolation makes use of Thiessen (or Voronoi) polygons to predict attribute values at unsampled locations based on a single, nearest, measured data point. Although a quick method of generating a grid of values from measured point locations, this method is not appropriate for phenomena that vary gradually over space: which is usually the case for environmental factors.

A more sophisticated, linear interpolation method, the *Inverse Distance Weighted* (IDW) interpolator assumes that each input point has a local influence on the point being predicted, and that the influence will diminish with distance although no provision is made to determine whether or not this assumption holds (Oliver & Webster, 1990). The algorithm therefore employs a weighting strategy where points closer to the location being predicted are given greater weight than those farther away. Most implementations of the algorithm allow for either a specified number of points, or for all points within a specified radius, to be used in the determination of the predicted value. A power parameter within the IDW interpolation algorithm controls the significance of the surrounding points upon the interpolated value with a higher power resulting in less influence being exerted from distant points.
The Spline interpolator is the computer equivalent of the draughtsman using a flexible ruler to fit a smooth curve through a series of points (Pavlidis, 1982). This interpolation method fits a minimum-curvature surface through the input points and can be thought of as bending a sheet of rubber to pass through the points, while minimising the total curvature of the surface. A mathematical function is fitted to a specified number of nearest input points, while at the same time passing through the point being interpolated. Mitasova et al. (1995) showed that interpolations using this method were effective for gently varying surfaces but have been found to be inappropriate if there are large changes in the surface within a short horizontal distance.

When there are lots of data points with which to work, most interpolation methods will give similar results (Burrough & McDonnell, 1998). If data are sparse then assumptions must be made concerning how well the sampling regime has captured the underlying variation. Choice of method and of associated parameters (number of points to include, search radius, weighting power function) can greatly affect the quality of the interpolated surface. One of the biggest drawbacks of the methods listed is that no direct estimation can be made of the errors associated with these interpolation routines and so no quality statement can be made concerning the generated surfaces. Another drawback of these more 'traditional' interpolation methods is that isotropy (or lack of directionality) is assumed within the data. Data collected for environmental research may not fit this pattern, for example where sediments are deposited in a linear fashion parallel to the course of a river, or where a prevailing wind direction has directly affected the deposition of an airborne pollutant.

4.5.2. Geostatistical interpolation

Geostatistical methods of interpolation, known as kriging, address some of the limitations inherent in other interpolation methodologies. With kriging an attempt is made to optimise, and to give some indication of errors within, the interpolation routine (Isaaks and Srivastava, 1989). The kriging methodology solves for the size,
shape and orientation of the interpolation window and allows for some estimate to be made of the errors associated with the interpolated values.

Kriging theory recognises that the spatial variation of a continuous variable, such as soil moisture or soil thickness, may be too irregular to be modelled by means of a simple mathematical function (Burrough, 1991). Regionalised variable theory (RVT) was developed largely by Matheron (1965, 1971) when he brought together earlier work in spatial statistics into a coherent body of theory. The theory comprises a deterministic component, a stochastic component and a random element such that the spatial variation of an attribute $Z$, at a position $x$ (in one, two or three dimensions) can be expressed as $Z(x)$ being the sum of: a structural component with a constant mean or a constant trend, $m(x)$; a random, spatially correlated component, $e'(x)$; and a random, spatially uncorrelated component (or noise), $e''$ in the form

$$Z(x) = m(x) + e'(x) + e''.$$

The implementation of this algorithm is dependent on two basic assumptions. The first assumption, often referred to as 'stationarity of differences', represents the fact that values of a given attribute for points closer together are likely to be more similar than those for points further apart. The second assumption, often referred to as 'variation of differences', represents the fact that attribute differences between sites will be a function of the distance separating those sites. These assumptions (of stationarity, and variation, of differences) define the requirements for Matheron's 'Intrinsic Hypothesis' of RVT. This means that once structural effects have been accounted for, the remaining variation will be homogeneous in its variation and differences between sites will be merely a function of the distance between them. Analysis of the semivariance can provide useful insight into these distance related functions. The semivariance, $\gamma$, can be determined from a set of sample data as:

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} (z(x_i) - (z(x_i + h))^2$$
where \( n \) is the number of pairs of sample points of observations of the values of attribute \( z \) separated by distance \( h \) (the lag). Plotting \( \gamma(h) \) against \( h \) gives the experimental variogram which provides information for interpolation, optimisation and the determination of spatial patterns. An example variogram is shown as Figure 4.4. It can be seen that at large values of the lag \( (h) \) the fitted curve levels off. This horizontal 'sill' implies that at these values of the lag there is no spatial dependence between data points. As the curve rises to the sill, the corresponding value of \( h \) (known as the range) indicates how large the interpolation window should be. An analysis of the semi-variogram and the determination of the best curve-fitting model is an interactive process which requires skill and judgement (Burrough and McDonnell, 1998).

\[ \gamma(h) \]

Figure 4.4 An experimental semi-variogram.

\[ \text{semivariance} \]

\[ \text{sill (} C_0 + C_f \text{)} \]

\[ \text{mugget (} C_0 \text{)} \]

\[ \text{range (a)} \]
When there is a clear, but not too large, nugget, and, where the range and sill are obvious, the spherical model is often the best fit to the observed variogram. Where the nugget and sill are clearly defined, but where there is only a gradual approach to the range, then the exponential model may be the most appropriate. Where the variation is smooth and the nugget is very small compared to the spatially correlated component, then the Gaussian model, with an inflection, may be most appropriate (Burrough and McDonnell, 1998). These models are known as \textit{bounded} or \textit{transitive} models, as they reach an upper bound referred to as the 'sill'. The presence of a sill might be indicative of discrete sub-regions, quite distinct from each other, but within which values are highly correlated (Oliver \textit{et al.}, 1989b). Unbounded variogram models, such as the linear model, typify attributes that vary at all scales (such as simple Brownian motion) and can be linked with the theory of fractals (Burrough, 1981). Figure 4.5 shows examples of the these variogram models. Further details of the theory and methodology underpinning kriging and semi-variogram modelling can be found in many texts relating to geostatistics (Oliver \textit{et al.}, 1989a; Gunnink & Burrough, 1996; Burrough & M'Donnell, 1998).

Research has been undertaken to compare the use of different interpolation methods for mapping soil properties. Warrick \textit{et al.} (1988) found kriging to be better than inverse distance weighting for mapping soil properties such as percent of sand, calcium content and infiltration rate. Laslett \textit{et al.} (1987) obtained more accurate predictions of soil pH using kriging rather than inverse distance weighting. Kravchenko and Bullock (1999) found kriging to perform better than inverse distance weighting in the modelling of soil potassium and phosphate concentrations. Gotway \textit{et al.} (1996) reported kriging to be an appropriate choice for the modelling of soil nitrate and organic matter. The performance of kriging can be significantly affected by the choice of the variogram model and by the spatial structure of the data (Leenaers \textit{et al.}, 1990; Kravchenko and Bullock, 1999) and an investigation of directionality in the data is critical prior to the selection of the variogram model to be employed (Burrough & M'Donnell, 1998).
The kriging method was employed in this research for modelling grids of topsoil thickness; volumetric soil moisture; and topsoil shear strength. Justification for the variogram models employed are given at appropriate points within the text.

4.6. Working with many criteria
The modelling of soil processes has an important role to play in evaluating the effects of land management on the environment and on crop yield, but the use of many models is limited by the large volume of input data required and the prohibitive costs of
obtaining such data. The spatial and temporal variability of soil properties means that their measurement is both time-consuming and expensive and the finer the resolution of the final model the more data are needed. Many soil parameters are affected by other physical, chemical or biological properties and it may therefore be possible to develop empirical relations in order to predict certain properties. The term 'pedotransfer function' was introduced by Bouma (1989) as being a means by which the data which we have may be able to be translated into the data which we need, essentially by means of a predictive function of certain soil properties from other (more easily available or cheaply measured) attributes. As Minasny and McBratney (2002) describe, these pedotransfer functions allow basic information from a variety of data sources to be translated into variables which may be expensive or laborious to determine empirically but consideration must be given to uncertainties in the predicted values.

4.6.1. Multiple regression

Many of the problems being researched by geographers, and especially those investigating the natural environment, are complex in nature and involve the consideration of a number of interacting variables. A range of statistical techniques are available which facilitate the exploration of complex data sets. Some techniques are concerned with the simplification or summarisation of large numbers of variables into a lesser number of synthesised parameters (e.g. factor analysis, principal components analysis and cluster analysis), while other techniques explore the relationships between variables and assist in the generation and testing of hypotheses (e.g. multiple regression and discriminant analysis). Although many of the multivariate techniques are based on the assumption that each individual data set approximates to a normal distribution, Chatfield and Collins (1980) have shown that most are fairly reliable under conditions of non-normality.

The multiple regression model attempts to explain the variation, or predict the value, of a single dependent variable ($y$) from a number of independent predictor variables.
These predictor variables may, or may not, be correlated between themselves, although, for modelling purposes, little correlation between independent variables is generally better (Shaw and Wheeler, 1994). The multiple regression equation takes the form

\[ Y = a + b_1X_1 + b_2X_2 + ... + b_iX_i + e \]

where \( a \) is the intercept value; \( b_1 \) to \( b_i \) are partial regression coefficients which, along with the \( X \) terms, represent the individual predictor variables; and \( e \) is the error term.

The partial regression coefficients are scale dependent and cannot be directly compared as they are dependent on the magnitude of the units of their predictor variables. To allow a direct comparison of the importance of each independent variable a beta weight (\( \beta_i \)) is determined by standardising each partial regression coefficient as follows

\[ \beta_i = b_i \left( \frac{s_{x_i}}{s_Y} \right) \]

where \( s_{x_i} \) is the standard deviation of the independent variable and \( s_Y \) the standard deviation of the dependent variable under consideration. The larger the value (either positive or negative) of each beta weight, the greater the importance of the associated independent variable in accounting for the behaviour of the dependent term.

When modelling data using multiple regression techniques, attention must be paid to issues of multicollinearity. This can occur if there is a high degree of correlation between any of the independent variables. If two highly correlated predictor variables are used in a multiple regression model it may appear that the second of these predictors adds little to the correlation coefficient or the predictive capacity of the regression equation. As the two predictor variables are highly correlated, using them both in the regression model essentially means that they each seek to explain the same variability. It follows that either might be used alone in the regression model without greatly reducing the resulting correlation coefficient. The regression model can best be
improved by including appropriate, but uncorrelated, predictors. In general the greater
the degree of multicollinearity, the less reliable are the partial regression coefficients
(Kendall, 1975; Johnston, 1978).

One possible solution to the problem of multicollinearity is the utilisation of factor
analysis or principal components analysis in order to group the independent variables
into synthesised 'new' variables. These new variables can then form the input to a
regression model, although care must be taken in their interpretation and manipulation.
An alternative approach, and the one that has been adopted in this research, is to adopt
a stepwise regression procedure whereby all possible regression models are explored
and variables added (or eliminated) until an optimum model is found i.e. one which
provides the best level of explanation with the smallest number of predictor terms.

The use of multiple stepwise regression and the pedotransfer functions obtained from
the empirical data are discussed in further detail in Chapter 7. Within this research
project, the objective was to find a means of generating layers of soil factors
(volumetric soil moisture, soil bulk density, topsoil depth etc.) which would then, in
conjunction with data of tree density and species variation across the site, form the
basis of a model for predicting optimum site locations for future tree planting and areas
for remedial action where the current planting regime has failed.

4.6.2. GIS and raster processing

One of the strengths of GIS as a modelling tool is the ease with which it is possible to
combine multiple layers of (raster) data using a range of methods from Boolean logic,
simple arithmetic functions or more complicated computational processes. These
techniques are used widely within GIS and details of the methods can be found in
many texts (Burrough and McDonnell, 1998; Chang, 2002).
The Boolean logical overlay is the simplest and perhaps one of the best-known GIS operations. Boolean logic rules (AND, OR, NOT, XOR etc.) are used to combine different layers giving a resultant 2-class map where, for each grid cell, the value is either TRUE or FALSE depending upon whether the various selection criteria have been met. For example, lets assume there is a requirement to find suitable areas for planting a particular tree species. The best conditions for this species are on slopes of less than 5 degrees and with a south facing aspect (between 135 and 225 degrees if North is at 0 degrees). Given raster layers of SLOPE and ASPECT, a Boolean expression could be formulated to produce a new raster layer (called SUITABLE) as:

\[
\text{SUITABLE} = (\text{SLOPE} < 5) \text{ AND } ((\text{ASPECT} \geq 135 \text{ AND ASPECT} \leq 225)).
\]

There are two obvious limitations to this Boolean logic approach: firstly, determination of threshold values for inclusion/exclusion may be subjective and; secondly, the assumption is made that all variables are equally important.

The binary result from a Boolean overlay approach may, in many cases be inappropriate or restrictive. The use of mathematically based overlays can overcome these restrictions. Using this method, weights can be assigned to the input layers in order to account for their differential impact on the result. This approach means that new data layers can be generated using quite complex mathematical formula. As an example, assume that statistical analysis of field data have shown that topsoil moisture is a function of topsoil thickness and slope with the following regression equation:

\[
\text{SOIL MOISTURE} = 0.61 - 0.04 \text{ SLOPE} + 0.02 \text{ SOIL THICKNESS}.
\]

Given raster layers of slope and soil thickness this algorithm could be used to generate a new raster layer of data giving a prediction of soil moisture across the area of interest.

Where threshold values are difficult to determine, or when a weighting strategy needs to be employed for the modelling of multiple layers of data, then linear combination
Multi-Criteria Analysis (MCA) can be employed. This technique allows for input layers to a model to be weighted according to their relative importance. The technique has been applied to site selection and location analysis problems for some time (Carver, 1991a) and the raster processing software essential for implementing the methodology is now available within most commercial GIS (Carver, 1991b). The weighting can be either a qualitative or quantitative score or rank.

The first stage in MCA is to identify the criteria to be used in the spatial model and the variables (or raster layers) being used to quantitatively represent those criteria. Each of these variables will then be standardised, most usually to a value of between 0 and 1. This standardisation of measurement scales allows for meaningful comparisons to be made between each of the data layers being processed (so, for example, 0 would represent poor conditions and 1 would represent maximum conditions for each variable). This standardisation process does not have to be a simple straight line transformation: value functions can be determined and used to standardise input variables, so if (for example) ideal slope values increased in suitability to 15 degrees, and then fell away again (as shown in Figure 4.6) the appropriate equation could be used to standardise the slope scores. More complex polynomial curves can also be used for standardisation.

![Figure 4.6 Using a mathematical equation to standardise SLOPE values for use with MCA](image)

\[ y = -0.0044x^2 + 0.1333x - 1E-16 \]
A weighting strategy can then be assigned to each of these standardised layers, the most common being based on their rank importance using either a rank reciprocal or a rank exponent strategy. Obviously interaction and independence between variables needs to be considered when applying weights. Expert judgement in the research field can often provide useful guidance, but additional sensitivity analysis can allow for different weighting strategies to be assessed in the light of the results produced. Many researchers have made use of the Analytic Hierarchy Process proposed by Saaty (1980) in order to establish weights for each of the input layers. This process provides an objective means of obtaining a weighting for each criteria by carrying out a series of pair-wise priority assessments of each input criteria against all the other input criteria: generating, in effect, a form of priority correlation matrix. Although widely used to assist with group decision making processes (Saaty, 1994; Peniwati, 1996), the approach offers potential support to other MCA-based research.

Regardless of how the weighting strategy is determined, once the input layers are aggregated and standardised, the resulting grid will contain values ranging from 0 to 1 indicating the extent to which the spatial modelling criteria have been met.

Raster-based modelling is used to great effect within this research project. The ranking and weighting strategies employed, and the use of raster based processing, are discussed in greater detail in the relevant sections of Chapter 7.

4.7. Environmental management using GIS

Environmental management has been identified as requiring three different kinds of information (Bregt et al., 2002). Firstly, data concerning the factors under investigation must be obtained in order to answer the 'what is where' questions such as 'where is the most productive soil?' or 'what is the dominant land use in this area?'. These data are obtained by means of survey and observation. Secondly, data must be gathered to
answer the 'what is changing where' questions in order to gain an understanding of the
temporal nature of the factors being studied. This may require that certain parameters
are monitored at selected spots over a period of time or that full areal surveys are
carried out at regular intervals. The main focus of much environmental modelling is an
attempt to provide the third type of data in order to answer the 'what will be where'
questions and allow for spatial and/or temporal projections to be made.

The 'what will be where' questions are the most difficult to answer as they require not
just an awareness of the initial (or current) state of the area under investigation but also
an understanding of the processes involved in bringing about change. These processes
are seldom simply biophysical, chemical or socio-economic, but more usually are an
interaction of many factors. GIS offers facilities to store and manipulate data in order
to facilitate answering the 'what is where' questions. The ability to store layers of data
and to query that data based on a time or date parameter allows an understanding of
'what is changing where'. A combination of this empirical data, with statistical and
spatial modelling routines provides a means of starting to explore answers to the 'what
will be where' questions.

In the context of this research, field survey data are collected and collated within the
GIS that describe a range of topographic and soil physical parameters. Regular
sampling of moisture and shear strength provide data to assist in the exploration of
both spatial and temporal variation in the topsoil. Statistical analysis of the
relationships between a range of parameters provide information for modelling and
prediction of soil and vegetation conditions. Further details of the data collected and
the analysis procedures are presented in the following chapters.
Chapter 5. Establishing a field study site

"The way to do fieldwork is never to come up for air until it is all over." Margaret Mead (1901-1978)

5.1. Mining and regeneration in the East Midlands

The East Midlands (comprising Derbyshire, Nottinghamshire, parts of Staffordshire, Lincolnshire, Northamptonshire, Leicestershire and Rutland) is an area rich in minerals, and the extraction and processing of these minerals have shaped both the landscape and the economy of the region. Dury (1963) in his regional geography of the East Midlands describes five distinct phases in the coal mining industry within this region between 1800 and 1960. The first phase (1800 to 1850) saw a gradual increase in output from ½ million to 2½ million tons a year. The second phase was one of more rapid increase with output reaching 18 million tons by 1890. Phase three saw output rise to 30 millions tons by 1913, after which there was a period of strikes and slumps, with output barely being maintained at this level. Renewed increase during the second World War raised annual production to 50 million tons a year (see Figure 5.1).

![Figure 5.1 Regional trend in coal output for the East Midlands (from Dury, 1963)](image-url)
Beynon et al. (2000) provide more recent figures for output from the National Coal Board/British Coal Corporation (NCB/BCC) prior to privatisation. Table 5.1 shows the output from deep mines and from opencast sites for a range of years up to 1994.

Table 5.1 NCB/BCC Deep mine and opencast output for the UK, 1971-1994 (from Beynon et al., 2000)

<table>
<thead>
<tr>
<th>financial year</th>
<th>deep mines (million tonnes)</th>
<th>opencast (million tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971/72</td>
<td>135.5</td>
<td>8.1</td>
</tr>
<tr>
<td>1975/76</td>
<td>114.5</td>
<td>10.4</td>
</tr>
<tr>
<td>1980/81</td>
<td>110.3</td>
<td>15.3</td>
</tr>
<tr>
<td>1985/86</td>
<td>88.4</td>
<td>14.1</td>
</tr>
<tr>
<td>1990/91</td>
<td>72.3</td>
<td>17.0</td>
</tr>
<tr>
<td>1993/94</td>
<td>42.7</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Deep mining and opencast mining have both played a significant role in the East Midlands region but, as in other parts of the country, many of the coalfields are now in decline and many sites are awaiting reclamation and redevelopment. One attempt to facilitate this redevelopment was the establishment of the National Forest (Sheail, 1997; Evans, 1998; Bell and Evans, 1998), an initiative announced in 1990 in an attempt to create a forest for the new millennium, which would redress some of the environmental damage and dereliction of land caused by industrial activity. The National Forest site links the ancient forests of Needwood in the west and Charnwood in the east (see Figure 5.2), covers 520 square kilometres, and spans three counties (Derbyshire, Leicestershire and Staffordshire). The Forest region is bounded by the major urban areas of Leicester and Derby (and Birmingham, further to the south), and has a history of mining, clay working, and industrial activity. The vision for the National Forest is to create a working landscape wherein ancient woodland can blend with new planting; farmland; open countryside; and the range of towns and villages (Countryside Commission, 1994).
Given the proximity of this environmental initiative to Loughborough University, it was decided that this research project should concentrate on the restoration of former opencast sites within the National Forest in order to provide useful insights for future programmes in this region. Lessons learned within this region will, hopefully, be able to be applied elsewhere across the country.

An investigation and visual assessment of three recently restored opencast mining sites in northwest Leicestershire, undertaken by the author in April 2000, supported the findings of Goodman (1998) that failure rates of up to 30% of planted stock could be found on restored sites. This investigation raised some of the issues relevant to this research: in particular, why failure occurs in certain sites; and, whether additional within-site monitoring and remediation could yield a higher return on investment in terms of ecological, financial, and aesthetic benefits. Visits were paid to the Coalfield...
North opencast site near the village of Heather, the Donnington Island former opencast site to the southwest of Ashby de la Zouch, and the former Lounge opencast mining site near the village of Coleorton. The Coalfield North site (grid reference SK400120) covers an area of 218 ha. Mining finished at the site in 1992 and the site was restored to amenity woodland in 1993/1994. This area now forms the Sence Valley regional park. The Donnington Island site (grid reference SK303172) covers 100 ha. of opencast workings and restoration to woodland occurred in the early 1990s. The Lounge opencast site near Coleorton (grid reference SK385185) covers an area of 63 ha. Mining at this site finished in 1992; soil replacement occurred during the following two years; and planting took place in 1995. By 2000, when the visits were made, the Coalfield North site was fully restored with some of the plantation areas appearing to be well established. There were parts of the site, however, which showed poor establishment by the planted species, and competition from gorse, thistle, and bramble was apparent in places. The Donnington Island site is not yet fully restored, but within the area that has been restored, the planted tree species show differential response across the site. Some regions show a high level of failure of uptake by the planted species. A similar pattern can be seen at the Lounge site where large areas of the plantation show total failure of the planted tree stock. Aerial photographs were obtained for all of these sites. The photographs were flown in July 1999. The timing of the photographs was fortuitous in that any healthy trees were at maximum foliage and more easily distinguishable from the surrounding surface vegetation. Figure 5.3 shows extracts of the aerial photographs for the three sites and clearly shows regions where tree establishment has failed to reach the desired potential.

Having established that restoration woodland schemes were not fully successful at any of the three sites visited, the decision was taken to explore one of the sites in greater detail. The purpose of this analysis was to try to determine the factors responsible for limiting tree growth and to explore the potential of within-site remediation of those factors. The Lounge site was selected as the study region for this project for a number of reasons. Firstly, the site was fully restored (unlike the Donnington Island site) and the planted trees had been in place for five years. Areas of tree failure were easily
distinguished and were apparent in patches across large areas of the restored site, indicating that the problem was not confined to a localised small sub-region within the restoration area. Secondly, information regarding the handling and working of soils at the Lounge site was readily available due to ongoing relations between the Department of Geography at Loughborough University and the landowner. Supplementary meteorological, soil, and water data were available from a small experimental field station that had been running on site since the mid-1990s. Thirdly, and finally, the site afforded ease of access for data collection and monitoring and, although affording public access, was not so well frequented as was the site at Coalfield North, thereby decreasing the likelihood of equipment being tampered with by members of the public.

Details outlining the geology of the field site; the soils and vegetation (both before and after mineral extraction); and the social and environmental implications of the site restoration are presented in the remainder of this chapter. Chapter 6 follows, giving details of the experimental design, the determination of sampling locations, and the data collection methods employed during the research.

5.2. The geology of north west Leicestershire

The topography of north west Leicestershire is determined by striking contrasts within the underlying rock. Figure 5.4 shows the geology of the area, with selected towns included for ease of geographical reference. Volcanic rocks, dating from the Precambrian period, to the east of the region give rise to rugged landforms which are mainly covered by heathland. To the west these features give way to a low and undulating clay plain. Smooth-sided valleys of younger rocks lie on top of the Carboniferous rocks that make up the South Derbyshire and Leicestershire coalfields. The coalfields are separated by the Boothorpe fault, with the Leicestershire coalfield being largely concealed beneath Triassic rocks.
Figure 5.3 Extracts from aerial photographs of three restored opencast sites in northwest Leicestershire, showing areas where tree establishment has failed. Coalfield North (top); Donnington Island (middle) and Lounge (bottom) sites. Photograph © Crown copyright. Ordnance Survey.
Only Middle and Lower Coal Measures are present, with the Kilburn being the lowest workable seam (Worssam and Old, 1988). Where the Lower Coal Measures reach the surface they have been mined by opencast methods as far back as the middle ages. The Main seam, near Coleorton village, was worked using bell pits (Worssam and Old, 1988). The lowest of the Triassic rocks are the Moira Breccia, outcropping to the west and south of the town of Moira. These are overlain by the Bromsgrove sandstone sequence and by Mercia mudstones.

Figure 5.4 The geology of north west Leicestershire (from Thompson, 1990).
5.3. The ecology and landuse of north west Leicestershire

An ecological survey of the region was undertaken by the Leicestershire Museums Service (1989) on a field-by-field basis with sites being graded as significant at a county, district, or parish level. Thompson (1990) reports the presence of significant unimproved pasture grasslands that provide ecological corridors along stream floodplains; and remnants of heathland which, although once widespread in the region, is now relatively rare due to agricultural improvement schemes. Woodland is also identified as a notable, though scarce, habitat, with Leicestershire having less than three percent woodland cover. Details of the ancient woodland sites in the region were compiled by Everett (1983) for a Nature Conservancy Council study of Leicestershire.

At the time of the first Ordnance Survey Series of the region (circa 1883) there were believed to be 313 hectares of ancient woodland in the region, by 1989 only 209 hectares remain. While a small proportion of this woodland was lost to agriculture and urban development, the majority, over 100 hectares, was lost to mineral extraction with more than 63 of these hectares being lost to the opencast operations at the Lounge site.

Opencast mining has a very obvious destructive impact on the landscape and environment, but it must be recognised that there is the potential for opencast mineral extraction to afford an environmental benefit through well-designed and implemented restoration programmes. Opportunities exist for the creation of new landscapes and new habitats, but, in order for this to be achieved, the planning; implementation; and aftercare of any restoration programme must be carefully monitored, and remedial action taken where necessary. The focus of this research is to offer a tool to assist in the monitoring and remediation of restored opencast sites.
5.4. Locating the study site

Having decided to focus the research on restoration programmes within the National Forest area, it was necessary to identify a suitable study site. A number of factors were identified as being of importance in determining the suitability of this study site. The selected site had to fall within a relatively small geographical area in order to effectively remove any local variation in altitude and climatic conditions. Conditions at the site had to offer some diversity in terms of the success of the woodland restoration programme. It was essential that some areas within the site showed evidence of successful tree planting while others showed failure. In order to understand the response of the soil moisture regime across the site, local rainfall data needed to be available, either by means of on-site observation, or from Meteorological Office gauging stations. The sampling regime was designed to cover a fifteen month period with, on average, bi-weekly visits, so the selected site needed to be close and easily accessible.

The restored Lounge opencast site in north west Leicestershire met all of these conditions and, in addition, was enhanced by the presence of a field monitoring station operated by the Department of Geography at Loughborough University, which provided continuous rainfall and channel runoff data. Historical data from this monitoring station were available for the four years preceding this research. These data provide useful checks on, and supplementary data to, the field data collected as part of this research.

5.5. Soils and landuse before mineral extraction

The study site lies to the north east of Ashby-de-la-Zouch between the villages of Coleorton and Lount as shown in Figure 5.5a. The extent of the area that would later be subjected to mineral extraction is delimited by the red boundary. On Figure 5.5b the blue shading indicates the extent of the fieldwork area of the current research project.
Figure 5.5a Location of the Lounge opencast site in relation to Ashby-de-la-Zouch
Figure 5.5b Detail of the Lounge opencast site prior to mineral extraction
The underlying mapping for both figures is the Ordnance Survey 1:25,000 series (1960) which gives an impression of the terrain prior to mineral extraction. Extracts from aerial photographs of the site can be seen in Appendix 2.3, showing the area as it was prior to mineral extraction (1953); and in Appendix 2.4, showing the area immediately prior to restoration (1991). Forming part of what was known as the 'Lounge' opencast workings during the time of mineral extraction by British Coal, the site will be referred to in future as the Lounge site. Prior to mining, the study area was part of the Staunton Harold Estate, and consisted of some 73 acres of mature oak woodland and approximately 20 acres of mixed coniferous woodland. Bracken (Pteridium aquilinum) was widespread and interspersed with the woodland (Blunt, 1998).

A soil study of the site was conducted by ADAS and accompanied the proposed (and revised) planning application in 1984/85. Figure 5.6 shows the soils found at the Lounge site and a brief description of the areas identified by ADAS is given below.

Areas labelled A comprise soils of the Ticknall series, developed on coal measure shales with a silty clay loam topsoil of 45 centimetres overlying silty clay loam or a silty clay subsoil. The profiles were found to be imperfectly drained with mottling present by 30 centimetres and prominent at 45 centimetres depth. Areas labelled B comprise soils of the Stanley series, similar in texture to those of the Ticknall series, but with a better subsoil structure and less prone to wetness problems. Again the profile was imperfectly drained with mottles present at 23 centimetres depth. The key physical attributes of the topsoil horizon of the Ticknall and Stanley series are given in Table 5.2. Areas labelled D comprise soils of the Staunton and Hodnet series. Staunton soils are developed on Triassic sandstones and mudstones where the bands of mudstone can cause impeded drainage. Fine sandy loam texture becomes heavier with depth and these soils comprise sandy clay loams below 25 centimetres. Hodnet series soils are developed on Triassic mudstones and commonly show a sandy silt loam texture throughout the profile. The profiles show imperfect drainage with grey colours present below 30 centimetres.
Figure 5.6 Soil types across the site prior to mineral extraction
(adapted from ADAS report: Lounge Proposed Opencast, Planning Application, 1984)
Table 5.2 Topsoil attributes for Ticknall and Stanley series soils (from Ragg et al., 1984), and Hodnet series soils (from Dubus and Brown, 2002)

<table>
<thead>
<tr>
<th></th>
<th>Ticknall Series (0-23 cm)</th>
<th>Stanley Series (0-25 cm)</th>
<th>Hodnet Series (0-20 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 600μm–2mm (%)</td>
<td>2</td>
<td>4</td>
<td>33</td>
</tr>
<tr>
<td>Sand 200-600μm (%)</td>
<td>1</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Sand 60-200μm (%)</td>
<td>9</td>
<td>12</td>
<td>33</td>
</tr>
<tr>
<td>Silt 2–60μm (%)</td>
<td>72</td>
<td>35</td>
<td>48</td>
</tr>
<tr>
<td>Clay 0.2–2μm (%)</td>
<td>11</td>
<td>32</td>
<td>19</td>
</tr>
<tr>
<td>Clay &lt; 0.2μm (%)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density (Mg m⁻³)</td>
<td>1.35</td>
<td></td>
<td>1.35</td>
</tr>
</tbody>
</table>

Areas labelled E comprise well-drained soils of the Bromsgrove series with a sandy loam texture to 60 centimetres, overlying the Triassic sandstone from which they develop. Fragments of sandstone were found throughout the profile, increasingly below 25 centimetres.

Areas labelled F comprise a mix of soils from the Worcester, Hodnet, Flint and Crew series which could not practicably be separated out at the scale of mapping. The Worcester series soils are developed on Triassic mudstones with a more clayey texture than those of the Hodnet series, while the Flint and Crew series soils are developed on reddish till. Soil textures include silty loam, silty clay loam, and very fine sandy clay loam overlying clay and clay loam. The profiles are imperfectly drained, with mottling present below 23 centimetres. Agricultural potential is limited due to this heavy texture and impeded drainage.

Areas labelled G are those areas comprising disturbed land from existing opencast workings, soil storage mounds, tips, and spoil heaps.
Soil reserves were deemed to be adequate for restoration, although, for agricultural end use, considerable quantities of soil making material would be required. The ADAS report recommended stripping depths of 0-150 mm for topsoil and 150-1000 mm for subsoil for each of these soil types under woodland areas. Stripping to a slightly greater depth (up to 250 mm for topsoil) was detailed for areas under agricultural use. National Coal Board geologists estimated that there existed the potential for recovering up to 200,000 m³ of soft sandstone from Triassic material to the south of the worked site which could provide a supply of soil making material.

A landuse study of the site conducted by MAFF and accompanying the planning application found that approximately 34% of the site was classified as non-agricultural land (being either mine workings or woodland); that there was no grade 1 or grade 5 agricultural land within the proposed site; that 35% of the area comprised grade 2 and grade 3a land, 23% was grade 3b and 9% was grades 3c and 4. The divisions for land classification (MAFF, 1966 and MAFF, 1976) were as follows:

Grade 1 land has very minor/no limitations to agricultural use and is deemed to be of exceptional quality;

Grade 2 land has some minor limitations with exclude it from the grade 1 category but is of high quality;

Grade 3 land is deemed to be valuable for a wide range of agricultural uses and is subdivided into:

   Grade 3a land has the moderate degree of limitation common to grade 3 but with some physical advantages leading to better agricultural performance than land in the remainder of the grade;

   Grade 3b land is capable of average production: typically of cereals and grass;

   Grade 3c land has some physical characteristics leading to poorer performance than other land in the grade;

Grade 4 land shows severe limitations due to (any combination of) adverse soil, relief or climate conditions and is of restricted potential;

Grade 5 land shows very severe limitations due to (any combination of) adverse soil, relief or climate conditions and is of very restricted potential.
5.6. Topography and soils following restoration

Mining development at the Lounge site commenced in September 1986 with the intention that extraction, backfilling, and restoration be completed by April 1992. An extension to the extraction permissions meant that mining continued until 1992, with the reinstatement of overburden and soils taking place during the summers of 1993 and 1994, and with planting commencing in 1995. The planning application (Ref. 92/0108/7) included details of procedures to be carried out regarding the removal, storage, and replacement of topsoil, subsoil and soil forming materials.

The planning application specified a range of restoration measures, which are understood to have been carried out at the site. All stored topsoil, subsoil, soil forming materials, and overburden were kept free of weeds and the storage mounds were seeded with grass to minimise soil loss. In order to minimise compaction, the stored mounds of topsoil did not exceed 5 m in height, while those of subsoil and soil forming materials did not exceed 15 m in height. None of the mounds of stored materials were traversed by heavy vehicles and machinery, and all movement of the soil took place when the soil was in a suitably dry condition.

On completion of mineral extraction, the land was contoured to conform with the surrounding land and the final topography was restored, as closely as possible, to that prior to mineral extraction. This means that some surface irregularities have been smoothed. According to the planning application the topography of the site was to be restored such that the site would be free from the risk of ponding or erosion, although evidence gained throughout this study has found this not to be the case across the entire site.

The overburden surface was ripped (using winged tines) to a depth of at least 900 mm below the surface of the subsoil thereby ensuring the removal of foreign objects (wire
rope, cable) and large stones; boulders; and other material which might have impeded drainage.

This also served to minimise compaction and to provide a reasonably level surface to receive the subsoil. All stones, and other deleterious material, have been removed from the site or buried at a depth of greater than 2 m from the surface of the topsoil.

The topsoil was spread to a thickness of 70-100 mm with sand being used as the main soil making material. Figure 5.7 shows the clear distinction between the topsoil and subsoil layers. On completion, the site was seeded with Italian rye grass to provide low level vegetation cover and help prevent runoff and erosion. Although fertiliser was added to the neighbouring area restored to agricultural production, none was added to the areas being returned to forestry.

The slopes indicated on the restoration plan drawings for the Lounge site were in the region of 1 in 30 (approximately 2 degrees). Forestry Commission guidelines recommend slopes of 1 in 10 (or approximately 6 degrees) for efficient internal

Figure 5.7 Profile of the upper layers of the restored soil.
drainage. A system of ridge and furrow drainage was, therefore, implemented on site following the Forestry Commission guidelines. The rationale and implementation of this procedure is described by Wilson (1985).

There are two water channels within the restored site: an upper channel feeding into an upper pond; and a lower channel draining from this pond to a second pond further to the north (and falling just outside the site selected for this study). The location of these drainage channels and ponds can be seen on the aerial photograph enclosed as Appendix 1. Although the lower channel has been restored to its existing location, the steep river cut banks are obviously missing. In order to protect the channels from erosion during stabilisation a permeable synthetic geotextile lining was installed and the bed and banks formed of interlocking textile panels.

5.7. Vegetation following restoration

A range of trees were planted across the site in lines which followed the ridge and furrow land forms. The planning application stated that the tree and plant species selected would mostly be suitably indigenous deciduous species. The planning application states '... the commercial forest areas consisting primarily of oak, cherry, alder, ash, lime, birch and sycamore with lesser numbers of beech, rowan, whitebeam and hornbeam. Suitable ground cover (including shrubs) will include such species as bird cherry, dog rose, field maple, crab apple and common pear. A number of bluebells, primroses and other small plants will also be introduced, and an appropriate forest seed mixture sown.' The planted areas were to be maintained during the five year aftercare period, with dead stock being replaced to achieve an eventual 80% take. The species breakdown for proposed for the site is shown in Table 5.3.

Larch had grown well on the site prior to mining, and was recognised as a commercial crop suitable to be harvested young (as fencing poles) or when mature (as construction
timber). Alder was recognised as a good pioneer and nitrogen fixing species. Poplar
was planted in wet areas under advice. Trees were planted so that two or three rows of
larch flanked four or five rows of mixed hardwoods as shown in Figure 5.8. Each
sapling was planted approximately 2 m along the ridge from its nearest neighbour
giving a density in the region of 0.2 trees per m$^2$. Larch was to be harvested first, and
the planting regime adopted was designed to afford access routes for subsequent
harvesting of the hardwood species. Following thinning and management, the final
planting density was anticipated as being approximately 200 trees per acre (or 0.05
trees per m$^2$). Sadly, growth of the planted tree species has been extremely variable
across the site and, to date, there is no evidence of either tree thinning or beating up
(replanting of failed stock) occurring on site.

Table 5.3 Proposed plant species at the restored Lounge site.

<table>
<thead>
<tr>
<th>Species</th>
<th>% planted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larch</td>
<td>Larix decidua</td>
</tr>
<tr>
<td>Oak</td>
<td>Quercus robur</td>
</tr>
<tr>
<td>Alder</td>
<td>Alnus glutinosa</td>
</tr>
<tr>
<td>Scots pine</td>
<td>Pinus sylvestris</td>
</tr>
<tr>
<td>Sycamore</td>
<td>Acer pseudoplatanus</td>
</tr>
<tr>
<td>Wild cherry</td>
<td>Prunus avium</td>
</tr>
<tr>
<td>Norway spruce</td>
<td>Picea abies</td>
</tr>
<tr>
<td>a mix of beech,</td>
<td>Fagus sylvatica,</td>
</tr>
<tr>
<td>small-leaved lime,</td>
<td>Tilia cordata,</td>
</tr>
<tr>
<td>poplar,</td>
<td>populus spp.,</td>
</tr>
<tr>
<td>crab apple,</td>
<td>Malus sylvestris,</td>
</tr>
<tr>
<td>goat willow</td>
<td>Salix caprea,</td>
</tr>
<tr>
<td>and field maple</td>
<td>and Acer campestre</td>
</tr>
</tbody>
</table>

Given that the imposed requirement for a five year aftercare scheme would have
elapsed in 2000, it is unlikely that these conditions will ever be achieved on the site.
The more successful trees are of acceptable size, but the poorest are small and stunted
and, in some areas, no trees have established successfully. There is no evidence across
the site of the planned bluebells and primroses, instead there has been a rapid incursion by many weed species: in particular spear thistle (*Cirsium vulgare*); creeping thistle (*Cirsium arvense*); common gorse (*Ulex europaeus*); and bramble (*Rubus fruticosus agg*). The bracken (*Pteridium aquilinum*) which was dominant at the site before mineral extraction is completely missing across the restored area.

The photographs shown in Figure 5.9 were taken in May 2001, and give some indication of the condition of the site at that time. The dense undergrowth of grasses and legumes, and the invasive gorse, are evident in the top image, while both pictures give a clear impression of the diversity in tree success across the area. The dried and dead stalks of the thistle are prominent in the foreground of both pictures.

![Plan of tree planting](image)

**Figure 5.8** Plan of tree planting implemented across the site following restoration.
5.8. Social and environmental aspects

Selman et al. (1991) identify nine key planning issues in relation to an afforestation scheme, which include: consideration of the recreational importance of the area for walking; the visual impact on the landscape; nature conservation potential and use of the area; any issues of archaeological significance; the impact on water courses; issues of public access and land ownership; any issues relating to sites of special scientific interest; and any agriculture concerns regarding the proposed afforestation. Not all of these factors are pertinent to a restoration scheme following opencast extraction, but they provide a general framework in which to investigate the restored site. There are no issues relating to sites of special scientific interest at the site. If such issues were to have existed at the site their investigation would have formed part of the original planning application prior to mineral extraction taking place. Similarly issues pertaining to land ownership and access rights are dealt with prior to the working of the site.

In relation to the restoration of the Lounge opencast site the remaining factors provide a useful set of descriptors by which to explore the impact of the restoration process. A number of the factors can clearly be inter-related: for example, public access will have an obvious impact on the recreational importance of the area, and will have associated impacts on the wildlife and nature conservation issues.

The Lounge site affords limited public access but nevertheless does play a role as an amenity woodland. A number of well marked, and well-surfaced, tracks allow public access through the restored site, and are suitable for bicycles; horses; and walkers. These tracks form clear boundaries between the planted areas and are labelled on the aerial photograph attached as Appendix 1. A few smaller footpaths with stiles lead through the planted areas. There is, however, little apparent use of the site for recreational walking. A number of factors may be contributing to this lack of use: firstly, the failure of the tree planting regime; secondly, the incursion by the many weed species as discussed in §5.7 (above) mean that the site is untidy to look at, and
unpleasant to walk through, especially during the summer months when these weeds are at their most vigorous; thirdly, the tendency of the soil to waterlogging for prolonged periods of the year makes it unattractive to walkers; fourthly, a lack of parking facilities, coupled with the distance from a population centre (approximately three miles along busy roads from the nearest town), may restrict the number of casual visitors; and finally, the proximity to the main A42 trunk road means that the site is adversely affected by traffic noise and pollution. The outbreak of foot and mouth disease during the time of this study, with the consequent closure of the footpaths across the county, has also served to keep visitor numbers down. In terms of the visual impact on the landscape the restored site has, compared with the opencast working, led to an improvement of the visual aesthetic of the area. When passing the site, on the major A42 trunk road, the impression is one of greenery that compares favourably with the landfill workings currently in operation in the vicinity. Closer inspection of the site, however, shows that tree establishment is patchy, and incursion by weeds, as discussed above, is rife. Figure 5.10 shows a photograph taken on site in August 2000, looking from east to west towards the A42 trunk road. A study of this photograph shows: in the far distance, the machinery operating on the neighbouring landfill; in the middle distance, a clear impression can be gained of the extent of the area in which tree planting has failed; while in the foreground, the competition between the trees, the gorse and the coarse grasses as the dominant vegetation cover can be clearly seen. The restored site does not compare favourably with the mature woodland on the neighbouring undisturbed site where no opencast extraction has taken place (refer to Appendix 1 where the undisturbed woodland can be seen to the bottom right of the photograph).

The fact that the site is not widely used by the public does afford some benefit. The site provides a relatively undisturbed wildlife habitat for a range of species. The shallow soils mean that the site does not readily support burrowing animals, although brown hares \((Lepus europaues)\) have been noted. Smaller mammals have also been sighted, including the common shrew \((Sorex araneus)\) and the field vole \((Microtus agrestis)\).
Figure 5.9 The restored Lounge open cast site, May 2001.
There is a sizeable resident population of skylarks (*Alauda arvensis*) and adders (*Vipera berus*) have been spotted basking in the sun on the site. In terms of the archaeological significance of the site, the opencast mineral extraction exposed some evidence of medieval and later mining. Early shaft mining, using timbers felled in the mid-15th century was exposed on the site (York & Warburton, 1990) and details of other finds are on display at the National Forest visitors centre. Following the disruption caused by the mineral extraction and the artificial nature of the restored environment little of archaeological interest now exists on the site.

The restoration process involved the replacement of the lower pond and the creation of an upper (balancing) pond with connecting drainage channels. The lower pond is stocked with a variety of freshwater fish, and is fished, and maintained, by a local angling club. The lower of the drainage channels has been restored to its previous location although the steep river cut banks are missing and the channel shape will remain unchanging. A permeable, synthetic, geotextile lining covers the sides and the bed of the drainage channels affording protection from erosion during a period of stabilisation. During the summer months the drainage channels dry out completely, but respond rapidly to high rainfall events. Periodic clearing of encroaching grasses; reeds; and sedges, and the constant variation in water level, mean that the channels offer little in the way of stable habitat for mammals or fish. No animal life has been noted in the channels on any visit to the site.

Part of the restored site has been returned to agricultural use and is currently in use as grazing for sheep and cattle. The areas to be returned to agriculture were afforded additional treatment at the time of restoration, with under drainage being installed and additional soil making materials and fertiliser being added. The regions to the northeast and to the south of the aerial photograph (Appendix 1) show those areas returned to an agricultural end use.
5.9. Site suitability for research

A thorough investigation of the site has been carried out in order to determine its suitability to support this research. Detailed information has been obtained, where possible, to describe the site conditions prior to, and subsequent to, mineral extraction taking place. The availability of detailed soils data provide useful information regarding the texture and condition of the soil used for restoration. The presence of an adjacent area of undisturbed woodland affords the opportunity for useful comparisons to be made between the natural and the artificial soil conditions in the area.

It is evident that there is considerable variation in the extent to which the desired range of tree species have been established across the restored site. The next stage of this research concerns the identification of test regions to reflect that variation. An analysis of a range of topographic and soil properties for these regions should provide useful data to assist in both the explanation of this variation, and provide an indication of possible remedial action that may be appropriate.
Figure 5.10. Conditions across the restored site, August 2000.
Chapter 6. Data collection

"It is a capital mistake to theorise before one has data."

*Sherlock Holmes from Arthur Conan Doyle, Scandal in Bohemia*

6.1. Introduction

As discussed at the outset of this thesis, the main foci of the research are, firstly, to explore factors affecting the success of tree planting on restored ground and, secondly, to determine whether empirical data can support a GIS-based model for optimising the level of planting success. Having identified the Lounge restoration site as being suitable for model development and testing, it was necessary to formalise the research objectives, and the methodology to be adopted. In order to fully understand the interactions between soil parameters and the success of tree planting across the restored area, criteria for a series of five investigations were drawn up as follows:

i. to investigate the patterns of vegetation success on areas of low planar slope (< 4 degrees) when all other factors (elevation, aspect and imposed surface drainage) are constant;

ii. to investigate the patterns of vegetation success on areas of medium planar slope (between 4 and 7 degrees) when all other factors are constant;

iii. to compare the vegetation success patterns found by investigations i and ii (above);

iv. to investigate the patterns of vegetation success where slope increases progressively from 0 to 10 degrees on a convexity;

v. to investigate the role of the imposed surface drainage regime on patterns of vegetation success by comparing areas where surface drainage assists downslope water movement with areas where surface drainage impedes downslope water movement.

In order to investigate each of these objectives, at least two samples points had to meet all of the predetermined criteria to satisfy the need for experimental replication.
To determine sampling locations that would allow a suitable test of each objective, a range of descriptive information was gathered and processed. Topographic information was obtained by means of a detailed survey of the study site and was used to determine elevation, slope and aspect. The density of vegetation cover and the patterns of imposed surface drainage across the study site were determined by means of a combination of analysis of aerial photographs and supplementary field survey. Once the experimental sampling points had been determined, data were collected to describe: the surface soil moisture content; shear strength; soil texture; and vegetation cover. Soil samples were collected and analysed for the major plant nutrients. Precipitation data for the study site was obtained both from gauges on site and from sites in the vicinity reporting to the Meteorological Office.

This chapter outlines the procedures for the selection of the sampling points; describes the data collection undertaken; and presents a preliminary overview of the data collected. Time constraints enforced the use of Microsoft® Excel for all statistical analysis and data presentation although this did impose limitations on the scope of analysis that could be undertaken.

6.2. Sample point selection and description

The field campaign was timetabled to extend from May 2000 to January 2002 with the bulk of the fieldwork being carried out during 2001. The outbreak of foot and mouth disease across the United Kingdom in 2001 meant that sampling during the months of February and March 2001 was curtailed.

The first task to be undertaken was the production of a detailed topographic survey of the study site. This was carried out in June 2000 using a motorised total survey station (the Leica TCA1800). Five control points were established and located using a high precision Leica System 200 Global Positioning System (GPS). From these five points, adequate coverage of the study site could be obtained. Each control point was visible
from at least two others, facilitating control of triangulation during the survey. A total of 473 points were surveyed for their positions in x, y and z planes. These points were used as the basis for generating a digital terrain model of the study site. The distribution of the survey points across the area and the positions of the control points are shown in Figure 6.1.

6.2.1. The digital terrain model

Digital terrain models (DTMs) have been used in geoscience applications since the 1950s (Miller and Laflamme, 1958) and have become a major constituent of geographical information processing. Often referred to as ‘digital elevation models’ when relief is the attribute being represented, the term ‘terrain’ allows for the possibility of including attributes other than topography. In a more general context, a DTM can represent any single attribute surface, be it that for air temperature, population density, or soil thickness. The data required for the generation of a topographic DTM are usually derived from ground survey, photogrammetric data capture or from digitised cartographic sources. In this study, a ground survey provided the relevant input data. Although ground survey is a relatively time consuming means of data capture, it is well suited to small area studies, tending to give a high level of accuracy and allowing inclusion of terrain points which are considered to be significant in the field.

A variety of data structures for DTMs have been used, but the most common are the TIN structure and the rectangular grid structure (Peucker, 1978). Regardless of the structure of the data points, an interpolation routine must be employed to estimate elevations for those regions where no measured data exist. Abundant literature exists on methods of interpolation for DTMs, but there is no agreed ‘best’ interpolation algorithm. Schut (1976), Lam (1983) and McCullagh (1988) offer an exploration of different methods but all agree that the quality of the DTM will depend on the distribution and accuracy of the original data points and the degree to which structural features and variation in terrain character can be taken into account.
Figure 6.1 Location of topographic survey and control points. Photograph © Crown copyright. Ordnance Survey.
6.2.2. The derivation of contours, slope, aspect and convexity

As the topographic survey points from the ground survey were not regularly spaced over the study site, the DTM was derived using a triangulated irregular network (TIN) structure. The topography of the study site is artificial and therefore shows a level of uniformity across the site. Discussion with the estate forester indicated that the river passing through the area, prior to mineral extraction, showed typical steep river cliffs on meanders along its course. Although the water course has been restored to its previous (general) location, this level of topographic detail is impossible to recreate during the restoration process.

As there were no complex terrain features to be taken into account and, given the adequate number and spread of survey data points, contours were derived using a function which interpolated a series of lines through the network of triangles making up the TIN. Every triangle edge was examined in order to see if a contour of predetermined interval passed through it. A linear interpolation between the edge endpoints was used to calculate a contour’s position along the edge.

Elevation values for the study site fall within the range 100-120 m with reference to mean sea level (MSL) as the vertical datum. An extract from the 1948 Ordnance Survey 1:25 000 series is presented in Appendix 2.1 and indicates the 375' (≈114 m) contour passing just to the south of the large pond (labelled 'lower pond' in Appendix 2.1 and in Appendix 1). The 425' (≈130 m) contour passes close to the southern extent of the delimited study site (approximately where the lower 'agricultural use' label is positioned in Appendix 1). This gives an overall range of 16 m across the study site. The surveyed elevation data ranged from 104 m to 121 m (MSL) giving a comparable range of 17 m, although the absolute values following restoration are some 10 m lower than the original topography. This difference in elevation may be due, in part, to vertical error inherent in the survey process. It is more likely, however, to be due to mineral extraction and the subsequent reinstatement of the topography using a reduced
The values within the aspect grid identify the down slope direction of the maximum rate of change in elevation from each cell to its neighbours. In effect, this can be thought of as the direction of slope, and is useful for determining the direction in which water might flow over the ground surface unimpeded. Values in the grid are given as compass directions where 0 represents grid north, 90 east, 180 south and 270 west. The area is effectively split into two sections, with the portion to the east of the main drainage channel facing predominantly west/northwest while the land lying to the west of the channel faces mostly east/northeast (see Figure 6.2). Slope values for these 4 m cells range from zero to nine degrees, with the majority falling between three and six degrees. The profile curvature was determined as an indication of the convexity or rate of change of the slope across the area. Figure 6.2 shows the derived contours and the grids of slope, aspect and profile curvature, while Figure 6.3 illustrates the spread of cell values for slope and aspect.

6.2.3. The variation in tree cover

The availability of an aerial photograph (scale 1: 6,000) flown in July 1999 proved a useful means of providing supplementary information about the study site without the need for time-consuming field survey.

The aerial photograph was scanned at a resolution of 2100 dpi. This image was then loaded into the ArcView GIS system and converted to British National Grid coordinates by means of a series of control points identifiable on both the scanned image and from the surveyed topographic data set. Routines within the GIS software allowed
the image to be rotated and shifted to align with the grid co-ordinate system being used. The imported greyscale image was converted from an image file to a grid file for further manipulation. An editing routine allowed for the selection of only those grid cells falling within the study site. The scanned image was saved in JPEG format. This format uses a combination of three separate bands (red, green and blue for colour images, and luminance, chrominance and greyscale for panchromatic images) each having values ranging from 0 to 255. By converting each of the three JPEG bands into ArcView grid files it was possible, based on experimentation, to select only those cells that corresponded with the areas of tree cover. These were cells with a value of between 50 and 90 in Band 1, a value of between 45 and 70 in Band 2, and a value of between 50 and 100 in Band 3. Given that the original photograph was flown in midsummer, foliage for all tree species was at a maximum, thereby giving a high chance of identifying areas of successful tree growth.

Scanning the aerial photograph at 2100 dpi gave a vegetation grid with a cell size resolution of 0.15 m. As the grids for elevation, slope and aspect had a cell size of 4 m it was necessary to re-sample the vegetation grid in order to change the resolution of the cells from 0.15 m to 4 m. A reclassification of the image was carried out using a software routine written in the ArcView Macro Language (AML) which generated a new 4 m grid by summing the number of original 'vegetation' cells falling within each new, larger, grid square. This total was then used to determine the percentage of each 4 m cell that could be classed as tree cover. Figure 6.4 illustrates the stages of this process from original photograph, through identification of cells representing tree cover, to the generation of the 4 m grid cells showing percentage tree cover.

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1 JPEG is a standard compression technique for storing full colour and grey scale images. The JPEG image extension within ArcView is based on the work of the Independent JPEG Group. Copyright © 1991-1996 Thomas G. Lane.

2 http://www.faqs.org/faqs/compression-faq
6.2.4. Selection of sampling points

An initial study of the area indicated that the spatial variability of tree vigour appeared to be systematic rather than random and so the selection of the sampling locations followed a two stage process. An initial determination was made, using the derived grids of slope, aspect and elevation, to identify regions with similar attributes. These regions were then overlain with the information from the aerial photograph showing tree density. All grid cells meeting the specified requirements for slope, aspect, elevation and tree growth were highlighted and three sample regions (A, B and C) delineated for further study. In order to identify sample points for more detailed analysis, an initial assessment of 'good' and 'poor' tree growth was undertaken based on the information available from the aerial photographs. This assessment was validated using empirical data on tree density gathered for each of the sample points and interpreted in light of the initial planting strategy employed at the time of restoration. Details of this validation are presented in Chapter 7.

Forestry Commission guidelines for restoration recommend slopes of approximately 6 degrees to ensure efficient surface drainage and advise that additional drainage be installed in areas of lesser slope. A ridge and furrow drainage system has been implemented across the study site but initial investigations had shown waterlogging of the topsoil in areas of low slope. This could be an indication that inadequate surface drainage is affecting the successful establishment of planted trees. In order to test the validity of this observation, twelve sampling points were selected which allowed for a comparison between the areas of low slope (up to four degrees) and the areas with higher slope values (bearing in mind that the topography of the restored ground showed no slopes of greater than ten degrees. The convexity of the terrain was also determined as this will directly impact the hydrology of the area, although the system of imposed surface drainage creates a micro-topography that will impact on water movement across the area (Pennock and de Jong, 1987; Moore et al., 1993; Cannon and Reid, 1993).
Figure 6.2 a. derived contours (in metres) and grids of slope (b), aspect (c), and profile curvature (d).
Figure 6.3 Histograms showing the spread of values for a) slope and b) aspect.
Figure 6.4 The determination of the percentage of tree cover in each 4 m cell:

a. The original aerial photograph, July 1999 (© Crown copyright. Ordnance Survey)
b. The reclassified JPEG cells showing location of trees
c. The 4 m cell grid showing percentage tree cover.
A positive curvature value indicates convexity (illustrated as light red in Figure 6.2d) while negative values indicate concavity (shown as pale blue in Figure 6.2d). The units determined are in 1/100 of the elevation units (metres). For hilly areas of moderate relief curvature values will normally lie within the range of −0.5 to +0.5, while in areas of extreme relief the range may be from −4 to +4 (Zevenbergen and Thorne, 1987). Curvature values across the study site ranged from −4 to +4 although more than 87% of grid cells had a curvature of between −1 and +1. The extreme values (< −3 and > +3) are all to be found at the periphery of the study site, these values being due to edge effects caused by the unavailability of elevation data beyond the area of interest.

The twelve selected points met the following criteria:

Category A points: two locations of good tree growth (ref. A2 and A10) and two locations of poor tree growth (ref. A1 and A9), north-easterly aspect, slopes between 2.0 and 4.0 degrees. Sampling points A1, A2 and A10 all fell within areas of concave slope while the slope at point A9 was slightly convex;

Category B points: two locations of good tree growth (ref. B6 and B8) and two locations of poor tree growth (ref. B5 and B7), west/north-westerly aspect, slopes between 4.0 and 7.0 degrees. Sampling points B5 and B7 fell within areas of concave slope while the slopes at points B6 and B8 were of a convex nature;

Category C points: four locations forming a transect from poor tree growth (ref. C3) through intermediate success (ref. C4 and C12) to good tree growth (ref. C11), east/north-easterly aspect, slopes between 4.0 and 7.0 degrees. Within region C, the slopes at points C3, C11 and C12 were concave while those at point C4 were convex.
These points fitted into the experimental design (outlined in §6.1 above) as follows:

i. low slope areas: all Category A points (A1, A2, A9, A10);

ii. medium slope areas: all Category B points (B5, B6, B7, B8);

iii. comparison of low and medium slope areas: all Category A points and all Category C points (C3, C4, C11, C12);

iv. change of slope along a single transect: all Category C points;

v. the role of the imposed surface drainage: all Category B points and all Category C points.

Although each sample point was marked by a peg placed at the grid references listed in Table 6.1, the sampling of soil parameters would be undertaken covering an area extending outwards five metres from that marker peg. Adopting a sampling scheme that extended out from the marker peg ensured that sufficient measurements were taken to provide a mean value that was representative of the soil conditions, and associated statistics on variance. The derived grids of slope, aspect and elevation had a cell size of four metres. In order to give a more representative indication of the topography covered by the soil sampling programme, a spatial filtering (or convolution) algorithm was applied to the values for slope, aspect and elevation in which the sample point was located. Mean values for slope, aspect and elevation were determined from the derived grids by using the 16 cells surrounding the peg, as shown in Figure 6.5. These mean values were taken as being representative of the sampling area. The location of the selected sampling points is shown in Figure 6.6 and their topographic parameters are given in Table 6.1. In order to test the model to be developed, additional data on topsoil thickness; soil moisture; and shear strength were collected periodically across each of the regions A, B and C. The use of these data to generate surfaces of topsoil thickness; shear strength; and soil moisture patterns are described below, while their role in the validation and testing of the algorithms developed in the modelling process is described in Chapters 7 and 8.
Field visits during the months of October, November and December 2000 were undertaken to locate and mark the position of these sampling points on the ground. Tests were carried out on the selected methods of data collection in order to give an indication of the time requirements necessary to meet collection targets. The sampling points were located on the ground using a hand-held GPS, with an estimated positional error of within 4 m. Pegs were used to mark the points for ease of future location and to remove the potential of any subsequent positioning error. Table 6.2 summarises the data collection undertaken at the study site.

6.3. Design and development of sampling schemes

Data were collected at each of the twelve sampling points during the months of October 2000 to January 2002. It had been anticipated that fortnightly samples could be obtained during the spring period, as the soil was entering its drying phase. However, the outbreak of foot and mouth disease in February 2001 meant that access to the study site was not possible from 19 February until 29 March, 2001. Thankfully, these months proved to be particularly wet, and the soil moisture content, monitored when sampling resumed, at the end of March was still at a comparable level to that registered in January of that year.
Table 6.1 Grid co-ordinates and topographic descriptors at the centroid of the 12 selected sample points.
Elevation, slope and aspect values are based on the mean of 16 grid cells surrounding the sample peg with the standard error given in brackets where appropriate.

<table>
<thead>
<tr>
<th>Point Reference</th>
<th>Easting</th>
<th>Northing</th>
<th>Elevation, m</th>
<th>Slope, degrees</th>
<th>Profile curvature</th>
<th>Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>438692</td>
<td>318551</td>
<td>109.9</td>
<td>3.0 (0.139)</td>
<td>Concave</td>
<td>NE</td>
</tr>
<tr>
<td>A2</td>
<td>438702</td>
<td>318515</td>
<td>110.8</td>
<td>3.0 (0.112)</td>
<td>Concave</td>
<td>NE</td>
</tr>
<tr>
<td>A9</td>
<td>438706</td>
<td>318546</td>
<td>109.2</td>
<td>2.8 (0.021)</td>
<td>Convex</td>
<td>NE</td>
</tr>
<tr>
<td>A10</td>
<td>438713</td>
<td>318483</td>
<td>111.4</td>
<td>3.3 (0.214)</td>
<td>Concave</td>
<td>NE</td>
</tr>
<tr>
<td>B5</td>
<td>438793</td>
<td>318539</td>
<td>109.0</td>
<td>5.4 (0.268)</td>
<td>Concave</td>
<td>W</td>
</tr>
<tr>
<td>B6</td>
<td>438832</td>
<td>318524</td>
<td>113.8</td>
<td>4.0 (0.145)</td>
<td>Convex</td>
<td>NW</td>
</tr>
<tr>
<td>B7</td>
<td>438803</td>
<td>318559</td>
<td>110.5</td>
<td>6.5 (0.061)</td>
<td>Concave</td>
<td>W</td>
</tr>
<tr>
<td>B8</td>
<td>438833</td>
<td>318549</td>
<td>113.8</td>
<td>6.2 (0.254)</td>
<td>Convex</td>
<td>W</td>
</tr>
<tr>
<td>C3</td>
<td>438689</td>
<td>318418</td>
<td>113.7</td>
<td>4.4 (0.107)</td>
<td>Concave</td>
<td>E</td>
</tr>
<tr>
<td>C4</td>
<td>438675</td>
<td>318415</td>
<td>114.9</td>
<td>4.7 (0.117)</td>
<td>Convex</td>
<td>NE</td>
</tr>
<tr>
<td>C11</td>
<td>438648</td>
<td>318411</td>
<td>116.8</td>
<td>4.8 (0.069)</td>
<td>Concave</td>
<td>NE</td>
</tr>
<tr>
<td>C12</td>
<td>438627</td>
<td>318411</td>
<td>118.2</td>
<td>5.7 (0.103)</td>
<td>Concave</td>
<td>NE</td>
</tr>
</tbody>
</table>

Table 6.2 Data collection undertaken across the study site.

<table>
<thead>
<tr>
<th>Extent of data collection</th>
<th>Data collected</th>
<th>Collection method</th>
<th>Number of data collection epochs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire study site</td>
<td>topography</td>
<td>field survey</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>tree density</td>
<td>from aerial photo</td>
<td>1</td>
</tr>
<tr>
<td>Regions A, B and C</td>
<td>topsoil thickness</td>
<td>core/ metal rule</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>topsoil bulk density</td>
<td>lab. analysis</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>topsoil moisture</td>
<td>ThetaProbe</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>topsoil shear strength</td>
<td>shear vane</td>
<td>2</td>
</tr>
<tr>
<td>Sample points</td>
<td>topsoil moisture</td>
<td>ThetaProbe</td>
<td>20</td>
</tr>
<tr>
<td>A1 - C12</td>
<td>topsoil shear strength</td>
<td>shear vane</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>tree diameter</td>
<td>digital callipers</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>topsoil texture</td>
<td>lab. analysis</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>topsoil bulk density</td>
<td>lab. analysis</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>topsoil chemistry</td>
<td>lab. analysis</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 6.6 Location of sampling sites.
Photograph © Crown copyright. Ordnance Survey.
On each of twenty site visits, data were collected for volumetric soil moisture by means of a Thetaprobe. The use of the Thetaprobe for the determination of volumetric soil moisture is described in Chapter 3. The prongs of the probe extend to six centimetres in length and effectively provide an estimate for the 30 cm³ column of soil within these prongs. The recorded values for volumetric soil moisture are therefore indicative of conditions within the top six centimetres of the topsoil horizon.

On four visits, soil shear strength and associated volumetric soil moisture were monitored by means of a hand shear vane and the Thetaprobe. The use of the shear vane for the determination of soil shear strength is described in Chapter 3. The 19 mm diameter vane was used as it allows for measurement of 0-120 kPa. The shear vane was forced into the soil, with minimal sideways movement, to a depth of approximately 60 mm, a marker on the vane ensuring that the correct depth had been reached.

In addition to this regular monitoring, soil samples were collected on two occasions for laboratory analysis of major plant nutrients, bulk density and Atterberg limits. Measurements of tree diameter on a range of representative trees were obtained in spring and autumn. Measurements of topsoil thickness were carried out across the three sampling regions (A, B and C) using an open sided auger and a detailed study of surface soil moisture and shear strength was carried out for these three regions on two separate occasions. Further details of the data collected can be found in the following sections.

6.3.1. Sampling scheme for soil moisture and shear strength

In order to minimise disturbance of the ground around each sampling point by the Thetaprobe and the shear vane, and to give a more representative set of data for each of the twelve points, a strategy was developed whereby the concentrated sampling of soil
parameters was undertaken in one of six sub-locations at each point, and never at the same sub-location on consecutive visits.

During the restoration process a surface drainage system of ploughed ridges and furrows was imposed across the entire area. The ridge and furrow landforms have a wavelength of approximately 1.5 metres and a residual relative relief of about 0.1 metre. Tree stock were planted along the ridge lines. Figure 6.8 gives an indication of the ridge and furrow topography while Appendix 1 shows the directionality of the ridges as the planted lines of trees can be seen clearly. Research by Cannon and Reid (1993) on relic ridge and furrow landforms in Cumbria showed that ridges were consistently drier than furrows. The mean difference in volumetric soil moisture (at a depth of ten centimetres) being $0.04 \text{ m}^3 \text{ m}^{-3}$ in October 1988 and $0.03 \text{ m}^3 \text{ m}^{-3}$ in November 1988. A series of investigations were undertaken across the study site, in October and November 2000, to explore the relationship between the volumetric soil moisture of the ridges and furrows. Moisture readings for the top six centimetres column of soil were obtained from seven points on two occasions, with 63 moisture readings being taken on the ridges and 42 moisture readings being taken in the furrows at each of the seven points on each visit. The data showed the furrows to be wetter on average by $0.05 \text{ m}^3 \text{ m}^{-3}$ in October and by $0.07 \text{ m}^3 \text{ m}^{-3}$ in November. The findings are comparable to those of Cannon and Reid (1993) given that the data for the study points are for topsoil moisture (as compared with data at ten centimetres depth) and that the shorter (1.5 metre) wavelength of the ridge and furrow landforms across the study site (compared with 2.8 metres) would promote greater shedding of water from the ridges to the furrows. Figure 6.7 shows the relationship between the volumetric soil moisture of the ridges and the furrows based on this investigation. The horizontal error bars show the standard error of the readings taken on the ridges (between 0.002 and 0.005) while the vertical error bars reflect the standard error of the readings taken in the furrows (between 0.001 and 0.005).
Figure 6.7 Volumetric soil moisture on the ridges and in the furrows (October/November 2000)
It is interesting to note from Figure 6.7, the convergence towards the 1:1 line as the volumetric soil moisture increases. This would indicate that, as conditions get wetter, voids within the soil are being filled regardless of any water redistribution due to the ridge and furrow drainage. Given these findings, it was decided that data collection for soil moisture would focus on the ridge forms. If conditions across the restored area were such that plants were being subjected to drought stress, then the driest conditions would be those experienced on the ridge tops. Conversely, if readings obtained on the ridges supported the premise that water logging of the top soil was limiting tree growth, then it can be accepted that worse conditions would be found in the furrows. The marker pegs, used to locate each sampling point, were placed on the ridge tops and all subsequent sampling of volumetric soil moisture and topsoil shear strength occurred on the ridges.

For each sample point the six sublocations for sampling were identified as follows:

- starting at the marker peg and sampling along a 5m transect up slope;
- starting at the marker peg and sampling along a 5m transect down slope;
- starting one ridge to the north of the marker peg and sampling along a 5m transect up slope;
- starting one ridge to the north of the marker peg and sampling along a 5m transect down slope;
- starting one ridge to the south of the marker peg and sampling along a 5m transect up slope;
- starting one ridge to the south of the marker peg and sampling along a 5m transect down slope.

The layout of these sampling transects is shown in Figure 6.8. On the first visit for data collection, transect type i. was employed, on the second visit type ii. was selected, and so on until there was a return to type i. on visit seven.
Soil moisture and shear strength readings were taken at 25 cm intervals along the line of the transect, starting at the marker peg and extending to five metres distant. At each 25 cm interval three readings were obtained from the relevant instrument giving a total of 63 readings from which to determine the measured parameter at each point and to account for variance in the measurements.

6.3.1.1. Soil moisture

A preliminary analysis of organic matter, determined by means of loss on ignition, showed that soil samples from the study site contained low levels of humic material (<15% on average in the top 20 cm, and <10% in the 20-40 cm layer). As expected on a restored soil, with a limited history of vegetation growth and decay, this was indicative of a mineral soil. For all readings across the study site, the Thetaprobe was set to use the default calibration relationship for mineral soils as detailed by Miller and Gaskin (1997).
Figure 6.10 shows a summary of the moisture data collected using the portable Thetaprobe, for each of the twelve sampling points. The box-and-whisker plots show the central tendency and the dispersion of the data collected. Plots are shown side-by-side for each of the sampling dates in 2001. The blue diamond, and extending blue line, show the position of the mean and the 95% confidence limits around the mean. The notched box shows the median, the lower and upper quartiles and the inter-quartile range (IQR). The presence of red crosses and circles on the plots indicate outliers in the data.

A small red cross indicates an observation more than 1.5 inter-quartile ranges (IQRs), defined as a near outlier, and a small red circle indicates an observation more than 3.0 IQRs (far outlier) from the quartiles (see Figure 6.9).

The diagrams in Figure 6.10 highlight a number of interesting patterns. Firstly, there is an obvious winter 'plateau' that can be identified for each of the sample points. Within this plateau, however, some of the points show an element of variation indicating a more rapid response to short periods of wetting and drying throughout the season.

The mean winter volumetric soil moisture (determined for the months of January to April and late-October to December, 2001) and the standard deviation about this winter mean are presented in Table 6.3.
Figure 6.10 Volumetric soil moisture for topsoil in sampling region A, January-December 2001.

Volumetric soil moisture (m$^3$ m$^{-3}$)

- Median
- 95% confidence interval
- 1Q range, upper/lower quartile

Range

Mean

95% confidence limit
### Volumetric Soil Moisture for Topsoil in Sampling Region B, January-December 2001

<table>
<thead>
<tr>
<th>Date</th>
<th>Sample Size</th>
<th>Mean</th>
<th>Median</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-Jan-01</td>
<td></td>
<td></td>
<td></td>
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**Legend:**
- **Range:** Difference between the highest and lowest values.
- **Mean:** Average value.
- **Median:** Middle value.
- **95% Confidence Interval:** Range of values within which the true mean is expected to fall with 95% confidence.
- **IQ Range:** Interquartile range, upper/lower quartile.
Figure 6.10: Volumetric soil moisture for topsoil in sampling region C, January-December 2001.
Table 6.3 Rates of change in volumetric soil moisture content.

<table>
<thead>
<tr>
<th>Point Reference</th>
<th>Mean winter volumetric soil moisture (m$^3$ m$^{-3}$)</th>
<th>Standard deviation</th>
<th>Winter to Summer Daily rate of change (m$^3$ m$^{-3}$)</th>
<th>Summer to Winter Daily rate of change (m$^3$ m$^{-3}$)</th>
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<td>0.011</td>
<td>-0.0028</td>
<td>0.0045</td>
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<tr>
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<td>0.009</td>
<td>-0.0037</td>
<td>0.0042</td>
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<tr>
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<td>-0.0030</td>
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<td>0.0020</td>
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<tr>
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<td>0.0046</td>
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<td>C12</td>
<td>0.392</td>
<td>0.023</td>
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<td>0.0029</td>
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</table>

The data in Table 6.3 show that points B8, C4, C11 and C12 have the lowest average soil moisture content during the winter months and the highest standard deviation indicating a greater variation in the soil moisture recorded at these points during these wet months. Based on field observation, these four points also appear to show some of the highest levels of tree establishment across the study site.

Figure 6.10 also illustrates the rate of change (or speed of wetting) of the topsoil between summer and winter conditions. A determination was made of the average daily rate of change in order to allow for comparison between the twelve points. The daily rate of change was calculated between 30th August and 12th September (13 days); between 12th September and 26th September (14 days); and between 26th September...
and 31st October (35 days) and an average of these three rates taken as being representative. The data are shown in Table 6.3. Again, points B8, C4, C11 and C12 show the slowest rate of wetting. This could indicate that redistribution of surface water (either by means of overland flow or by downward water movement through cracks and fissures) is more effective at these points as compared to points (such as A9 and C3) which wet at a faster rate and, once wet, show little variation across the entire winter period. On determining topsoil bulk density for each sample point (see §6.3.2), points B8, C4, C11 and C12 were found to have less compact soil than many of the other points (Table 6.5) and thereby possibly afford greater downward movement of water through the soil profile. The relationships between soil moisture and the soil physical properties are explored further in Chapter 7.

Similarly, the data in Figure 6.10 illustrate the rate of change as the soil dries throughout the spring and early summer period. A determination was again made of the average daily rate of change during this drying phase. The daily rate of change was calculated between 26th April and 9th May (13 days); between 9th May and 30th May (21 days); and between 30th May and 14th June (15 days) and an average of these three rates taken and presented in Table 6.3. Points B8, C4, C11 and C12 show the greatest rate of drying during this period. This may, again, be an indication of effective redistribution processes at work in these areas. However, given that these points have the highest percentage tree cover, this loss of moisture from the topsoil could reflect a period of vigorous tree growth. These apparent relationships between patterns of soil moisture and the successful establishment of trees are explored in more detail in Chapter 7.

Figure 6.10 also shows the response of the topsoil moisture regime to a number of significant rainfall events occurring during July and August. On the day prior to sampling in July 2001, approximately 68 mm rain fell across the study site. In the days between the sampling visits of 30 July and 15 August, 44 mm of rainfall was recorded (Appendix 3 shows the daily rainfall for 2001 at the study site). This rainfall is
reflected in the increased topsoil moisture readings recorded on 17 July and 15 August, 2001. Sample point B7 showed the most pronounced response to the July rainfall event indicating an inability of this point to rapidly shed surplus rainfall and highlighting it as a potential site for winter waterlogging.

In order to further explore moisture patterns across regions A, B and C the decision was taken to carry out a number of more detailed moisture surveys. The sampling schemes for these surveys are given in §6.3.5 below. An exploration of these data in relation to soil structure, soil chemistry and vegetation success will be presented in subsequent chapters.

6.3.1.2. Soil shear strength

Figure 6.11 shows a summary of the soil shear strength data collected, at six centimetres depth, for each of the twelve sampling points. The interpretation of the box-and-whisker plots is as described above. In terms of shear strength of the topsoil layer, points B6 and B7 show the greatest range in measured shear strength values during the sampling period. The values for point B6 range from 23 kPa in February 2001 to 128 kPa in July. Point A1 showed the least variation in values, from 14 kPa in May 2001 to 64 kPa in July 2001.

The graphs in Figure 6.11 show a number of interesting features. In all cases the spread of shear strength values recorded during the drier months (May and July) is greater than that recorded when the topsoil is wet. This tight distribution of shear values during the winter months might be indicative of the soil approaching its liquid limit: the soil moisture being so high that shear strength is at its minimum. Determination of the soil liquid limit (Table 6.5) enabled a comparison with winter volumetric soil moisture and showed that, with the possible exceptions of points A1 and A9, soil moisture conditions were not approaching the liquid limit.
Figure 6.11 Topsoil shear strength (at 6 cm, \( n = 63 \)) for sampling region A, January-December 2001.
Figure 6.11 Topsoil shear strength (at 6 cm, \( n = 63 \)) for sampling region B, January-December 2001.
Figure 6.11 Topsoil shear strength (at 6 cm, \( n = 63 \)) for sampling region C, January-December 2001.
Figure 6.12 Topsoil shear strength and volumetric soil moisture content.
In order to investigate further, mean shear strength value was plotted against mean soil moisture value for each sample point for each sampling date (giving a total of 48 sets of data). Figure 6.12 shows this graph of shear strength on soil moisture. The graph highlights the spread of shear strength values recorded in (relatively) dry soil conditions, but there appears to be a point (at soil moisture values in the order of 0.4 m$^3$ m$^{-3}$) where the trend is towards the asymptote. An exploration of these data in relation to soil structure, soil moisture and vegetation success will be presented in subsequent chapters.

6.3.2. Sampling scheme to obtain topsoil cores for laboratory analysis

A similar approach to that employed for soil moisture was adopted for the collection of topsoil samples. These samples were collected systematically from the area surrounding each sample point. When cores were collected for chemical analysis, five cores were obtained (with volumes of 100 cm$^3$) using an open-sided auger at each of the twelve sampling points. The cores were collected to be representative of the soil from two to ten centimetres depth in the profile. Although the cores were sealed and transported back to the laboratory within 4 hours, the top and bottom sections of the samples (two centimetres at the top and any of the core below the ten centimetre depth) were discarded in order to minimise any chemical effects due to exposure to air. The removal of the top two centimetres also facilitated the removal of any vegetative and root material. One sample was taken close to the marker peg, one approximately a metre upslope of the peg on the same ridge, and another one metre downslope on the ridge. The remaining two samples were taken on the same contour as the marker peg but from the ridges on either side. This sampling layout for the soil cores is shown in Figure 6.13.

The five soil samples for each point were bulked, this bulked sample being air-dried, well-mixed, sieved and the < 2 mm fraction retained for chemical analysis by means of the Palintest system. Five repeats of each chemical analysis were undertaken from the bulk sample for each point. Given the normal range of values identified as being
required to support plant growth (Table 3.3 and Figure 6.14), and the comparatively low standard error (Table 6.4) of the samples, the mean of the five replicate analyses was taken as being representative. The range of values for the major soil nutrients were comparable to those reported by Scullion and Malinovszky (1995) and by Merrill et al. (1998). The liquid and plastic limits were determined using air-dried soil passing through a 420 micron sieve. Organic carbon was determined using the Walkley-Black method on air-dried soil passing a 500 micron sieve. Particle size distribution was determined using the Sedigraph (as described in Chapter 3) on soil washed through a 250 micron sieve following removal of the organic material. The material retained in the sieve was dried and any material passing through a 2000 micron sieve included in the sand fraction of the particle size analysis. Any material larger than 2000 microns was discarded from this analysis.

Topsoil bulk density (Mg m$^{-3}$) was determined via the core method (Blake and Hartage, 1986) with cylindrical metal samplers being used to preserve in situ samples. The central portion of each core was used in the determination of bulk density in order to remove any possible distortion due to compaction at either the top or the bottom of the sampling cylinder. The mean of the five cores analysed for each point was taken as being representative of the bulk density at that sampling point. Two sites were identified within an area adjacent to the study site where no coal extraction had taken place. These two sites can be seen on the areal photograph, Appendix 1.
At each of these points, five cores were taken and bulk density determined as above. These data allow an assessment to be made of the impact of mineral extraction and restoration on soil bulk density by affording a means of comparison between the disturbed and the undisturbed soils.

Tables 6.3 and 6.4 provide a summary of the data for the chemical and physical analyses carried out.

Soil pH across the study site ranged from 4.16 to 7.02 with most of the sample points falling within the normal range for plant growth of 5.0 - 7.5 (Bradshaw & Chadwick, 1980). The sample points with a strongly acid topsoil (points B6, B8 and C12) are all points with comparatively high tree density and although these points show high levels of exchangeable aluminium it would appear that levels toxic to plant growth have not been reached. Although none of the sample points show pH levels higher than pH 7 (neutral conditions), those points with the highest pH values (all of the Region A points and point C3) show the lowest tree densities.
Table 6.4. Summary mean values of chemical analyses \(^1\) of topsoil for each site with the standard error given in brackets.

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<td>(6.124)</td>
<td>(1.079)</td>
<td>(0.139)</td>
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\(^1\) Analysis of nitrate, ammonium, phosphate, potassium, calcium, magnesium and aluminium utilised the Palintest Soil Test System.

\(^2\) Values are given as mg 100g\(^-1\) to allow for ease of comparison with other published data with figures quoted as ppm or mg 100g\(^-1\).

\(^3\) pH was determined using a 2:1 solution of de-ionised water:soil.

\(^4\) Conductivity was determined using a soil:water ratio of 1:5 and measured using an electrical conductance meter.

\(^5\) Nitrate N was extracted using 1M ammonium chloride at a soil:water ratio of 1:25, reduced to nitrite and colour reacted to form a red azo-dye.

\(^6\) Ammonia, calcium, magnesium and aluminium were extracted using 1M potassium chloride at a soil:water ratio of 1:5 and colour reacted.

\(^7\) Phosphate was extracted using 0.5M sodium bicarbonate at a soil:water ratio of 1:25 then complexed with ammonium molybdate to form a coloured solution.

\(^8\) Potassium was extracted using 0.1M magnesium acetate at a soil:water ratio of 1:25 then complexed with sodium tetraphenylboron to form a turbid white solution.

\(^9\) Organic carbon was determined using the Walkley-Black method.
Table 6.5. Summary mean values of physical analyses of topsoil for each site with the standard error given in brackets.

<table>
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<th>Site Ref.</th>
<th>Plastic limit&lt;sup&gt;1&lt;/sup&gt; %</th>
<th>Liquid limit&lt;sup&gt;1&lt;/sup&gt; %</th>
<th>Plasticity Index&lt;sup&gt;2&lt;/sup&gt; %</th>
<th>Bulk density Mg m&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Topsoil thickness mm</th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
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<td>44 (1.02)</td>
<td>22</td>
<td>1.41 (0.02)</td>
<td>129</td>
<td>27</td>
<td>35</td>
<td>38</td>
</tr>
<tr>
<td>A2</td>
<td>25 (0.22)</td>
<td>51 (1.37)</td>
<td>26</td>
<td>1.31 (0.01)</td>
<td>173</td>
<td>22</td>
<td>35</td>
<td>43</td>
</tr>
<tr>
<td>A9</td>
<td>20 (0.01)</td>
<td>44 (0.80)</td>
<td>24</td>
<td>1.44 (0.03)</td>
<td>137</td>
<td>33</td>
<td>32</td>
<td>35</td>
</tr>
<tr>
<td>A10</td>
<td>26 (0.20)</td>
<td>57 (0.77)</td>
<td>31</td>
<td>1.32 (0.04)</td>
<td>191</td>
<td>22</td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td>B5</td>
<td>27 (1.65)</td>
<td>57 (0.21)</td>
<td>30</td>
<td>1.45 (0.02)</td>
<td>106</td>
<td>21</td>
<td>38</td>
<td>41</td>
</tr>
<tr>
<td>B6</td>
<td>27 (0.69)</td>
<td>56 (1.25)</td>
<td>29</td>
<td>1.33 (0.03)</td>
<td>183</td>
<td>30</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>B7</td>
<td>29 (0.09)</td>
<td>58 (1.51)</td>
<td>29</td>
<td>1.34 (0.01)</td>
<td>114</td>
<td>32</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>B8</td>
<td>30 (0.52)</td>
<td>60 (0.39)</td>
<td>30</td>
<td>1.28 (0.02)</td>
<td>164</td>
<td>34</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>C3</td>
<td>25 (0.17)</td>
<td>46 (0.87)</td>
<td>21</td>
<td>1.44 (0.01)</td>
<td>163</td>
<td>19</td>
<td>42</td>
<td>39</td>
</tr>
<tr>
<td>C4</td>
<td>27 (0.14)</td>
<td>57 (0.51)</td>
<td>30</td>
<td>1.29 (0.04)</td>
<td>188</td>
<td>20</td>
<td>38</td>
<td>42</td>
</tr>
<tr>
<td>C11</td>
<td>26 (0.49)</td>
<td>55 (0.34)</td>
<td>29</td>
<td>1.29 (0.01)</td>
<td>199</td>
<td>25</td>
<td>42</td>
<td>33</td>
</tr>
<tr>
<td>C12</td>
<td>25 (0.09)</td>
<td>49 (1.65)</td>
<td>24</td>
<td>1.31 (0.01)</td>
<td>203</td>
<td>22</td>
<td>42</td>
<td>36</td>
</tr>
</tbody>
</table>

<sup>1</sup> determined as 100 * (weight of water)/(weight of dry soil)

<sup>2</sup> fine earth (< 2 mm) only
Figure 6.14 Nutrient concentrations recorded at each sampling point
(Note: Bradshaw & Chadwick data have been converted from ppm to mg 100g\(^{-1}\) soil)
Figure 6.14 shows the nutrient concentrations recorded at each of the sample points with reference to the normal range for successful plant growth as reported by Bradshaw & Chadwick (1980). These graphs illustrate that the concentration of nitrogen (in both nitrate and ammonia forms) across the entire study site tends towards, and in many cases falls below, the limits identified as being required for plant growth. Phosphate; potassium; magnesium; and calcium levels fall within, or exceed, the required levels.

The findings from the chemical analysis indicate that, as discussed in Chapter 3, nitrogen deficiency may be a cause of poor response of trees across the study site. A more detailed exploration of these data in relation to soil moisture and vegetation success will be presented in subsequent chapters.

6.3.3. Sampling for tree diameter

Details of the planting regime employed across the study site are given in Chapter 5, with Table 5.2. showing the percentage breakdown of species planted. As there is extreme diversity in tree response across the study site, and, in order to reflect the major species planted, it was decided to concentrate the tree survey carried out for this study on four species: larch, oak, alder, and Scots pine, which together account for 80 percent of the trees planted. Although it was not possible to locate all of these species at all twelve of the sampling points (particularly in those areas showing higher failure rates of tree growth), it was possible to obtain data for a total of 110 trees.

A representative set of trees was selected at each of the twelve identified sampling points. Where possible, a mix of tree species was selected and, as far as was possible, a minimum of three replicates for each species was sampled at each point. Table 6.6 shows the number of each species monitored at each point and gives the percentage breakdown for each of the four species being investigated. Selected trees ranged in
height from between one and four metres, and each species showed a great deal of variation in height variation over a small area.

The universal convention for tree mensuration is to employ the 'Diameter at Breast Height over Bark' (DBHOB) technique whereby measurement is taken at a fixed height (known as Breast Height) of 1.3 metres above the ground surface. Given the range of tree height, coupled with the young age of the stands, the use of this DBHOB standard height was inappropriate for many of the trees across the study site. The nearest approximation, which could be applied consistently, was to obtain measurements of trunk diameter at one metre above ground surface for all species. Diameters were measured using digital callipers, in the spring and autumn of 2001, to give an indication of stem growth during one growing season.

Table 6.6 Number of trees by species sampled at each point.

<table>
<thead>
<tr>
<th>Point Reference</th>
<th>Larch</th>
<th>Oak</th>
<th>Alder</th>
<th>Scots Pine</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>A2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>A9</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>A10</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td><strong>Total Region A</strong></td>
<td><strong>10 (43.5%)</strong></td>
<td><strong>4 (17.4%)</strong></td>
<td><strong>6 (26.1%)</strong></td>
<td><strong>3 (13.0%)</strong></td>
<td><strong>23</strong></td>
</tr>
<tr>
<td>B5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>B6</td>
<td>8</td>
<td>2</td>
<td>7</td>
<td>0</td>
<td>17</td>
</tr>
<tr>
<td>B7</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>B8</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td><strong>Total Region B</strong></td>
<td><strong>17 (43.6%)</strong></td>
<td><strong>5 (12.8%)</strong></td>
<td><strong>13 (33.3%)</strong></td>
<td><strong>4 (10.3%)</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td>C3</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>C4</td>
<td>6</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>C11</td>
<td>7</td>
<td>0</td>
<td>6</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>C12</td>
<td>6</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td><strong>Total Region C</strong></td>
<td><strong>20 (41.7%)</strong></td>
<td><strong>0</strong></td>
<td><strong>16 (33.3%)</strong></td>
<td><strong>12 (25.0%)</strong></td>
<td><strong>48</strong></td>
</tr>
<tr>
<td><strong>3-region total</strong></td>
<td><strong>47 (42.7%)</strong></td>
<td><strong>9 (8.2%)</strong></td>
<td><strong>35 (31.8%)</strong></td>
<td><strong>19 (17.3%)</strong></td>
<td><strong>110</strong></td>
</tr>
</tbody>
</table>
A summary of the collected data is given in Table 6.7. For sampling regions A and B, the pine trees showed the greatest percentage increase in stem diameter during this growing season, while for area C, larch showed the highest percentage increase. In March 2001, within region A, the alders were of greatest diameter at an average of 98 mm, while the oak trees had an average diameter of just 31 mm. A similar pattern was found within region B with the alders having a mean diameter of 99 mm and the oak trees having an average diameter of 34 mm. In region C the pine trees were of noticeably greater stem diameter than those in regions A and B, with a mean diameter of 168 mm.

In terms of increase in diameter, the greatest growth (at 16mm) was recorded for the alders within region B representing an increase of 16%. The greatest increase in diameter (in percentage terms) was recorded as 21% for the pine trees within region B. The oak trees monitored within regions A and B showed no measurable growth during this growing season. Research by Gingrich (1971) indicated an average annual diameter growth for oak of 5 mm over a range of age, site and stand conditions. The small sample size available for oak means that little weight can be placed on these growth statistics; however the very fact that few oak trees have established successfully across the study site may indicate that inappropriate decisions on species were taken at the time of planting. Planting at the Lounge site took place in 1995 so the measurements taken represent the growth status six years on from planting. Allowing for a similar annual increment in diameter of between 10 and 16 mm per year, the alders are of a comparable size to those recorded by Phares et al. (1975) who found diameters of 137 mm in trees nine years after planting and 201 mm fourteen years after planting. Scots pine has been found to show massive variation in growth rate between trees at a single site (Rudolph and Lemmien, 1959) and published figures are not readily comparable with those recorded at the Lounge study sites. Nevertheless, the pine trees monitored in all three regions showed an average increment in diameter of 13 mm. Diameter data were available for larch trees of 19 years standing and indicated diameters in the order of 130-150 mm (Schmidt, 1978). If growth continued at the rate measured for the study site, the larch trees on this restored site would exceed those
values. Larch diameter growth has been found to be very sensitive to stand density and growth rates have been found to decrease significantly with increased density of planting (Schmidt, 1966). So, it is likely that the successful larch trees will be of a diameter similar to those recorded by Schmidt (1978).

Further exploration of these data in relation to the physical, chemical and hydrological properties of the soil of each area will be presented in subsequent chapters.

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>Number of trees</th>
<th>Mean Diameter (mm) March 2001</th>
<th>Mean Diameter (mm) October 2001</th>
<th>Diameter change (mm)</th>
<th>Diameter change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Region A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larch</td>
<td>10</td>
<td>57</td>
<td>67</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>Oak</td>
<td>4</td>
<td>31</td>
<td>31</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Alder</td>
<td>6</td>
<td>98</td>
<td>112</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Pine</td>
<td>3</td>
<td>83</td>
<td>98</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td><strong>Region B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larch</td>
<td>17</td>
<td>91</td>
<td>102</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Oak</td>
<td>5</td>
<td>34</td>
<td>35</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Alder</td>
<td>13</td>
<td>99</td>
<td>115</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Pine</td>
<td>4</td>
<td>70</td>
<td>85</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td><strong>Region C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larch</td>
<td>20</td>
<td>96</td>
<td>107</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Oak</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alder</td>
<td>16</td>
<td>116</td>
<td>126</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Pine</td>
<td>12</td>
<td>168</td>
<td>176</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>

6.3.4. Sampling scheme to determine topsoil thickness

Soil cores were extracted from 127 sampling points across regions A, B and C. The distance between sampling points was paced out to be roughly 10 m and the coordinates of the sample point registered using the hand-held GPS. Figure 6.15 shows the location of each sampling point within the three regions. At each point, three cores, taken 10 cm apart, were extracted from the top of the ridges using an open sided auger and the thickness of the topsoil measured with a metal rule. The average measurement from the three cores was recorded as the topsoil thickness at that point.
Figure 6.15 Location of topsoil thickness survey points.
Photograph © Crown copyright. Ordnance Survey.
Figure 6.16 Generated grids of topsoil thickness.
Region A covers an area of approximately 2100 m$^2$ in which 35 sets of values were recorded. For region B, an area of approximately 3800 m$^2$, 63 sets of values were recorded while for region C, being slightly smaller at 1800 m$^2$, 29 sets of values were recorded. When the co-ordinates of the sample points were registered on the GIS the average distance between samples for each location was determined as being eight metres. Given the estimated positional error of the hand held GPS to be in the order of four metres, these sampling locations are, on average, between six and ten metres distant from their nearest neighbour.

These data were used to interpolate surfaces of mean soil thickness for the three regions (A, B and C). A visual inspection of a number of directional variograms showed no apparent anisotropy in the data and therefore the omni-directional variogram was used in the subsequent kriging analysis (Goovaerts, 1997). A study of the semi-variogram for the data points indicated that a Gaussian kriging algorithm with a maximum lag of 40 m was the most appropriate model. Details of the use of the kriging for interpolation can be found in Chapter 4. The generated surfaces are shown in Figure 6.16 with the exploratory semi-variograms being included for reference as Appendix 4. Sample sizes in the order of 200 points are recommended in order to generate an appropriate semivariogram (Myers, 1993) although smaller sample sizes have been used in soil science applications (Eltaib et al., 2002). In this research the sample sizes use to interpolate surfaces of topsoil thickness, volumetric soil moisture and shear strength fall below this recommended value. A subset of the field-sampled data was (temporarily) withheld from the kriging process and used to validate the interpolated surfaces. This validation indicated adequate sample sizes for the spatial extent being modelled.

For region A, modelled topsoil thickness ranged from 128 to 199 mm with a mean of 165 mm and a standard error of 2. Region B had modelled topsoil thickness ranging from 91 to 190 mm, a mean of 156 mm and a standard error of 2. Modelled topsoil thickness for region C ranged from 159 to 209 mm with a mean of 192 mm and a
standard error of 1. Topsoil thickness values for each of the twelve sampling points (A1 - C12) were extracted from this modelled surface by averaging the values of the nine grid cells surrounding each marker peg. These values, and the modelling to which they form an input, are discussed further in Chapter 7.

6.3.5. Sampling scheme for localised detailed soil moisture and shear strength survey

In order to provide more information regarding patterns of topsoil moisture across the three study regions, two detailed surveys of volumetric moisture content and shear strength of the topsoil were carried out over the same ground as that of the topsoil thickness survey. The first of these surveys was undertaken early on 6th September 2001, when the topsoil moisture was at a minimum. The second survey was carried out early on 7th December 2001 when topsoil moisture had returned to field capacity. These surveys were carried out to provide data as input to interpolation routines. These point source data underpin the derivation of ‘surfaces’ of soil moisture and shear strength, which are later used, within the GIS, at the modelling stage of this research.

In the September survey, data were collected for 175 sampling points across regions A, B and C. The co-ordinates of the sample points were registered using the hand-held GPS. Figure 6.17a shows the location of each sampling point within the three regions. At each sample point, three readings were taken with the Thetaprobe, each ten centimetres apart along the top of a ridge, and the values recorded. The mean of the three readings was taken as representing the volumetric soil moisture content at each sample point. Similarly, three readings were taken along the ridge top, each 10 cm apart, with the shear vane and the mean of the three readings was taken as indicating the topsoil shear strength for each sample point. Field-testing of this sampling strategy was carried out in conjunction with regular data collection at the twelve sample points in order to obtain timings for data collection. This field testing (36 data collections for soil moisture and 12 data collections for shear strength, each comprising 3 readings) showed that the three samples provided a mean value that fell within 1 standard error of the mean determined using the regular sampling procedure (see §6.3.1 above) in 34 cases for soil moisture (94%) and in 9 cases for shear strength (75%).
Figure 6.17 Location of topsoil moisture/shear strength survey points:

a. September 2001
b. December 2001

Photograph, © Crown copyright. Ordnance Survey.
Given the constraints of carrying out this more detailed site survey, where all data had to be collected on the same day, in the same weather conditions and with as little temporal variation as possible, it was accepted that the mean values determined from three readings provided an acceptable indicator of soil conditions.

In this first survey, 49 sets of data were recorded to cover region A, 88 sets for region B and 38 for region C. These data were used to interpolate surfaces of volumetric soil moisture and shear strength for the three regions.

As was found for topsoil thickness, there was no evidence of anisotropy in a visual inspection of the directional variograms for either the soil moisture or shear strength data. In all cases the appropriate omni-directional variograms were used for subsequent analysis. An exploration of the semi-variogram for the moisture data for September showed an exponential curve, with a maximum lag of 50 m, to be the most appropriate kriging model for interpolation. The generated surfaces are shown in Figure 6.18a.

Within region A, modelled volumetric soil moisture ranged from 0.268 to 0.333 m$^3$ m$^{-3}$ with a mean of 0.304 m$^3$ m$^{-3}$ and a standard error of 0.002. Region B had modelled moisture values ranging from 0.246 to 0.332 m$^3$ m$^{-3}$, a mean of 0.279 m$^3$ m$^{-3}$ and a standard error of 0.001. Modelled moisture values across region C ranged from 0.277 to 0.337 m$^3$ m$^{-3}$ with a mean of 0.300 m$^3$ m$^{-3}$ and a standard error of 0.002.

Curve-fitting of the semi-variogram for the September shear strength data showed that an exponential kriging algorithm with a maximum lag of 40 m was most appropriate for interpolation. The generated surfaces are shown in Figure 6.19a. Within region A, modelled shear strength ranged from 121 to 125 kPa with a mean of 123 kPa and a standard error of 0.06. Region B had modelled shear strength values ranging from 123 to 128 kPa, a mean of 124 kPa and a standard error of 0.04. Modelled shear strength values for region C ranged from 123 to 125 kPa with a mean of 124 kPa and a standard error of 0.04.
In the December survey, data were collected for 161 sampling points in total. Figure 6.17b shows the location of each sampling point within the three regions. In this survey, 43 sets of data were recorded to cover region A, 82 sets for region B, and 36 for region C. Again, an exponential kriging algorithm was employed for the volumetric soil moisture model, and surfaces were interpolated based on the point mean soil moisture recorded. The generated moisture surfaces are shown in Figure 6.18b. For region A, modelled volumetric soil moistures ranged from 0.367 to 0.436 m\(^3\) m\(^{-3}\) with a mean of 0.397 m\(^3\) m\(^{-3}\) and a standard error of 0.002. Region B had modelled moisture values ranging from 0.391 to 0.452 m\(^3\) m\(^{-3}\), a mean of 0.413 m\(^3\) m\(^{-3}\) and a standard error of 0.001. Modelled moisture values for region C ranged from 0.360 to 0.408 m\(^3\) m\(^{-3}\) with a mean of 0.384 m\(^3\) m\(^{-3}\) and a standard error of 0.001.

An exponential kriging algorithm was employed for the shear strength model, with surfaces being interpolated from the point mean recorded values for shear strength. The generated surfaces are shown in Figure 6.19b. For region A, modelled shear strength ranged from 25 to 37 kPa with a mean of 30 kPa and a standard error of 0.27. Region B had modelled shear strength values ranging from 22 to 30 kPa, a mean of 27 kPa and a standard error of 0.13. Modelled shear strength for region C ranged from 27 to 37 kPa with a mean of 32 kPa and a standard error of 0.20.

6.3.6. Precipitation data

The presence of a rain gauge within the study site afforded precipitation data for several years prior to this field work being undertaken, but one requirement of this study was the need to explore rainfall patterns in the area at the time of restoration and planting of the site, i.e. before the on-site rain gauge was established. A method was developed whereby rainfall for the study site was predicted using data from the neighbouring sites of Blackbrook Reservoir and Staunton Harold Reservoir, all of which return data to the Meteorological Office (MO). These neighbouring sites fall within 10 km of the study site at the Lounge opencast site and are shown in Figure 6.20 in relation to the field study site.
Figure 6.18a. Generated grids of topsoil moisture: 6th September 2001.
Figure 6.18b. Generated grids of topsoil moisture: 7th December 2001.
Region A

Region B

Region C

Figure 6.19a. Generated grids of topsoil shear strength: September 2001.
Figure 6.19b. Generated grids of topsoil shear strength: December 2001.
MO data were obtained by means of the British Atmospheric Data Centre (BADC) website\(^1\) and a range of regression analyses were carried out to explore any correlation between the recorded rainfall at the MO sites and at the study site. The data were plotted as scatter graphs and any obvious anomalies were removed from the regression analysis. These outliers were deemed to be indicative of faulty equipment, data input error, or operator error. The presence of a strong correlation between sites (with R\(^2\) values ranging from 0.80 to 0.95), allowed missing rainfall data at the study site to be predicted with confidence from the MO data. Data for the years 1998 - 2000 were available from the on-site rain gauge and were used in the statistical procedures. A summary of the results is given in Table 6.8.

The highest R\(^2\) value (0.95) was returned from the correlation between the on-site data and the data for the Blackbrook site and so, where possible, data for this site were used to predict rainfall values for the Lounge site. Where MO data were missing for the Blackbrook site, the data from the Staunton Harold site were used. Failure of the data-logging equipment attached to the on-site rain gauge occurred during the field season of 2001. The regression equations detailed below were again used to fill any gaps in the on-site rainfall record.

<table>
<thead>
<tr>
<th>Description</th>
<th>R(^2)</th>
<th>No. observations</th>
<th>Model equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lounge against combined B'brook &amp;</td>
<td>0.89</td>
<td>611</td>
<td>Lounge = 0.10 + 0.95 B'brook + 0.04 Staunton H.</td>
</tr>
<tr>
<td>Staunton H.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lounge against Staunton H.</td>
<td>0.80</td>
<td>702</td>
<td>Lounge = 0.27 + 0.91 Staunton H.</td>
</tr>
<tr>
<td>Lounge against B'brook</td>
<td>0.95</td>
<td>695</td>
<td>Lounge = 0.16 + 0.97 B'brook</td>
</tr>
</tbody>
</table>

\(^1\)http://www.badc.rl.ac.uk/
A summary of the rainfall record for the site for the years 1993 - 2001 is given in Table 6.9, while Figure 6.21 shows the cumulative rainfall for these years, and the mean cumulative rainfall for the nine years of data processed.

Soils at the study site were reinstated during the summer months of 1993 and 1994 and planting was started in 1995. Figure 6.22a shows the monthly rainfall patterns for each of these years. It is clear from the diagram that the summer months (April-July) of 1993 recorded above average rainfall at the site.

### Table 6.9 Monthly rainfall at the Lounge site, 1993 - 2001.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>60</td>
<td>86</td>
<td>96</td>
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<td>24</td>
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<tr>
<td>February</td>
<td>13</td>
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<td>57</td>
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<td>67</td>
<td>13</td>
<td>50</td>
<td>76</td>
<td>71</td>
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</tr>
<tr>
<td>March</td>
<td>11</td>
<td>72</td>
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<td>79</td>
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<td>82</td>
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</tr>
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<td>April</td>
<td>113</td>
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<td>16</td>
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<td>111</td>
<td>82</td>
<td>131</td>
<td>115</td>
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</tr>
<tr>
<td>May</td>
<td>65</td>
<td>72</td>
<td>30</td>
<td>35</td>
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<td>22</td>
<td>68</td>
<td>89</td>
<td>77</td>
<td>56</td>
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<tr>
<td>June</td>
<td>72</td>
<td>15</td>
<td>10</td>
<td>26</td>
<td>117</td>
<td>132</td>
<td>91</td>
<td>35</td>
<td>23</td>
<td>62</td>
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<tr>
<td>July</td>
<td>81</td>
<td>29</td>
<td>13</td>
<td>32</td>
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<td>18</td>
<td>95</td>
<td>38</td>
<td>132</td>
<td>43</td>
</tr>
<tr>
<td>August</td>
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<td>9</td>
<td>55</td>
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<td>60</td>
<td>97</td>
<td>62</td>
<td>62</td>
<td>56</td>
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<tr>
<td>September</td>
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<td>145</td>
<td>112</td>
<td>11</td>
<td>33</td>
<td>109</td>
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<tr>
<td>October</td>
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<td>29</td>
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<td>138</td>
<td>84</td>
<td>122</td>
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<tr>
<td>November</td>
<td>74</td>
<td>79</td>
<td>62</td>
<td>93</td>
<td>80</td>
<td>38</td>
<td>41</td>
<td>113</td>
<td>35</td>
<td>72</td>
</tr>
<tr>
<td>December</td>
<td>118</td>
<td>89</td>
<td>74</td>
<td>55</td>
<td>65</td>
<td>79</td>
<td>77</td>
<td>74</td>
<td>34</td>
<td>79</td>
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<td><strong>Total</strong></td>
<td><strong>854</strong></td>
<td><strong>812</strong></td>
<td><strong>556</strong></td>
<td><strong>551</strong></td>
<td><strong>663</strong></td>
<td><strong>898</strong></td>
<td><strong>991</strong></td>
<td><strong>920</strong></td>
<td><strong>858</strong></td>
<td><strong>781</strong></td>
</tr>
</tbody>
</table>

Values in blue were modelled using data from Blackbrook reservoir

This could mean that, despite the best endeavours of the contractors, soil was handled and site restoration occurred in wetter than ideal conditions. Looking at the monthly rainfall patterns for 1996 and 1997 (Figure 6.22b), it is worth noting that, for the spring months of March, April and May, the site received lower than average rainfall. These two years represent the first two growing seasons for trees planted on site following restoration. This, lower than average, rainfall could have had two possible effects on the newly planted trees. Firstly, working to their advantage could be the fact that it is unlikely that the soil suffered from prolonged waterlogging during these periods of active growth, such a condition being identified by Bending and Moffat (1999) as being instrumental in depressing growth rates.
Figure 6.20 Location of Meteorological Office rain gauges and study site.
Reproduced from Ordnance Survey map data by permission of Ordnance Survey, © Crown copyright.
Figure 6.21 Cumulative daily rainfall at the Lounge site, 1993 - 2001.
Figure 6.22a. Monthly rainfall at the Lounge site, 1993 - 1995.
Figure 6.22b. Monthly rainfall at the Lounge site, 1996 - 1998.
Figure 6.22c. Monthly rainfall at the Lounge site, 1999 - 2001.
Secondly, the winter following planting in 1995 was one of below average rainfall at the site (Figure 6.22a), followed by this relatively dry spring in 1996. This might mean that the growth of the young root systems of the recently planted trees, especially if restricted by compaction, might not have kept pace with the diminishing level of available soil water (Binns, 1980) and the saplings may have been exposed to some drought stress. An analysis of the physical characteristics and moisture patterns of the topsoil across the site will provide evidence as to whether those areas which have failed to support tree growth coincide with the areas where topsoil is susceptible to drought stress or waterlogging, or show signs of poor soil structure.

6.4. Summary

This chapter presents details of the field sampling regime and associated analyses that were designed and undertaken in order to explore the relationships between tree growth and the physical and chemical properties of restored soils.

The raw data, collected from the field, have been collated and initial processing undertaken in order to provide a descriptive overview of conditions across the study site. Data have been presented which describe the topographical variation across the site, the changes in soil chemistry, the physical soil properties and the hydrological regime as they vary from one sampling point to another within the area of study.

The next stage of the research is to process these data, seek to find, and then to explain, inter-relationships between the various factors in an attempt to determine the optimum conditions for successful tree growth on the site and possible explanations for local failure. The following chapters take up this challenge and explore how statistical analyses and geographical information systems can provide useful tools for the processing, visualising and modelling of data.
Chapter 7. Data analysis

"If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties."
Sir Francis Bacon (1561-1626)

7.1 Introduction

The fieldwork phase of this research has provided data for more than 30 topsoil variables at twelve distinct sampling points across the study site. These twelve sampling points are identified on Figure 6.6 and are referenced by a letter A, B or C (to denote the wider region into which they fall) and by a number between 1 and 12 (thereby giving a unique reference code for each point). In order to give an initial indication of the relative success of tree establishment at each of the sample points, a count was made of the number of trees (of all species) falling within five metres of a central peg. This five metre circular zone covers an area of 78.54 m$^2$ and the number of trees per m$^2$ is determined by dividing the tree count by 78.54. The site restoration plan specified a final planted density of 200 trees per acre, which is equivalent to 0.05 trees per m$^2$. It was anticipated that, with maintenance and replacement of dead stock, an eventual uptake of 80% would be achieved. Planting was undertaken at the site in 1995 with the compulsory aftercare period extending until 2000. The field work for this research was conducted in 2000/2001 and, allowing for thinning and management which may have been carried out as part of the aftercare procedures, by this stage it can be accepted that sample points with a tree density of 0.04, or fewer, trees per m$^2$ (which is 80% of the ideal stocking density, and equates to three trees or less within five metres of the peg) have failed to achieve the required stocking density and are deemed to be poor areas of tree establishment. In contrast, points with tree density values of greater than 0.04 have achieved the planned stocking density. It must be noted, however, that there is no record of any aftercare or maintenance having been undertaken at the site and so the current tree density must be seen in light of the original planting density (refer back to Chapter 5, §5.7) of 0.2 trees per m$^2$. As the focus of this research is to relate levels of tree success to a number of other factors, this
variable has been included, where appropriate, on the data tables presented to allow easy reference to the relative tree status of each sample point.

Each pair of sampling points in regions A and B is designed to include one point in which tree density is low and another in which tree density is higher. Within each region there are two such 'pairs' of data points. The corresponding pairs for comparison between low and high tree density are A1 with A2; A9 with A10; B5 with B6; and B7 with B8. The data in the tables is presented in this order for ease of reference between sampling points. Region C has been organised slightly differently as the points here follow a transect from low tree density (C3), through intermediate (C4) to high density (C11) and back to intermediate again (C12). For comparing low and high tree densities, point C3 can best be paired with point C11. The rationale and descriptions of the sampling points can be found in Chapter 6, (§6.2.4) while the location and spatial extent of each region can be seen by referring to Figure 6.6.

Region A, located in the central part of the study site, lies between two drainage channels in an area of low slope (less than 3.0 degrees) and with a north-easterly aspect (mean azimuth of 51°). The imposed system of drainage rills lies on a bearing of 19 degrees (i.e. to NNE) and therefore works with the slope to help move surface water towards the drainage channels. Within region A, sampling points A1 and A9 fall in areas where few, if any, trees have successfully established, while points A2 and A10 are located in areas showing greater levels of success. It must be noted, however, that these 'successful' points within region A have tree density values (0.06 trees per m²) which are only slightly higher than their 'unsuccessful' counterparts (0.04 trees per m²) and have much lower tree density values than the successful points in regions B and C (0.11 to 0.17 trees per m²).

Region B, to the east of the study site lies on ground having a predominantly westerly aspect (mean azimuth of 277°) and slopes of between 4.0 and 6.5 degrees. The ploughed drainage rills in this part of the study site lie on a bearing of 281 degrees (i.e.
to the NNW) and, again, work with the slope to promote surface water movement into the drainage channels. Within region B, sampling points B5 and B7 are located in areas of poor tree establishment while points B6 and B8 show more vigorous tree growth.

Region C, to the west of the study site, lies on ground with a north-easterly aspect (mean azimuth of 64°) and with slopes in the order of 4.0 to 6.0 degrees. In this part of the study site, the imposed system of drainage rills lie on a northerly bearing and therefore, in some parts, run almost parallel with the land contour and offer no downslope assistance to surface water movement. This region contains sampling points C3, C4, C11 and C12. Of these sampling points, C3 is located in an area where few trees have established, C4 and C12 show moderate levels of success and C11 shows the highest level of planting success.

Data collected for these points describe the physical structure, the chemistry, and the annual moisture regime of the topsoil. The required outcome from an analysis of these data is a new index of tree growth potential: essentially, a model to allow a quantitative prediction of tree success potential derived from the relations between a range of topographic and soil parameters.

In order to test the effectiveness of the model, algorithms developed from the data for the twelve sampling points (A1 to C12) need to be tested on data collected for the remainder of the three regions (A, B and C). A further 25 sampling points were randomly selected in each of the three regions and formed the basis for intermittent sampling of topsoil moisture and shear strength. Determinations of topsoil bulk density were made at 12 of these 25 points within each region. The position of these additional sampling points, and details of the data collection undertaken, are discussed further in §7.3.
The modelling process is broken down into a series of four distinct stages:

- an exploration of the spatial patterns of each of the measured variables and any cross correlation found between variables (including tests for normality prior to the use of any parametric statistics);

- the development of regression equations based on the data collected at each of the twelve sampling points, which are then used to predict values over a wider spatial area;

- an exploration of the spatial and temporal patterns of these variables in relation to patterns of tree growth across the study site;

- the development of an index of tree survival/tree growth potential, leading to the identification of areas for optimal tree success and, conversely, an identification of those areas which could be improved given some level of remedial action.

These stages will be described in more detail in the following sections.

7.2 Exploration of the data

Details of the sampling strategy employed, and some preliminary findings describing topsoil physical, chemical and moisture properties at each of the twelve sample points have been presented in Chapter 6.

Earlier research has shown that a deterioration of the soil structure limits the successful establishment of trees on restored ground (Bending et al., 1991; Scullion & Malinovszky, 1995; Andrews et al., 1998). Scullion and Malinovszky (1995) indicate that there is a need for better use to be made of data describing basic soil properties in order to allow practical decisions to be taken regarding species suitability and ameliorative measures. Given that the physical condition of the soil and the consequent effect on the soil moisture regime has been found consistently to limit tree growth, the
main focus of this research is to explore spatial patterns in physical soil properties. Some simple chemical analyses have been undertaken in order to ensure that nutrient supply is not limiting tree growth across the study site. This separation of the physical and chemical variables has led to two distinct sets of analysis being carried out: one exploring the relations between the physical soil properties and one describing the chemical status of the soil. For each of the twelve sample points, data were collected for 17 variables describing the topography and the physical properties of the topsoil. Seven further descriptors were computed from the collected volumetric soil moisture data, with a further two variables determined from the measured shear strength data and the particle size distribution data. This gives a total of 26 measures of the soil and the 'physical' environment as shown in Table 7.1.

Table 7.1. Measured and computed descriptors of topographic and topsoil physical characteristics.

<table>
<thead>
<tr>
<th>Measured parameters</th>
<th>Derived parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>trees per m²</td>
<td>topsoil moisture range</td>
</tr>
<tr>
<td>angle of slope*</td>
<td>topsoil moisture modal value</td>
</tr>
<tr>
<td>direction of slope (aspect)*</td>
<td>topsoil moisture mode: summer</td>
</tr>
<tr>
<td>slope along ploughed ridges</td>
<td>topsoil moisture mode: winter</td>
</tr>
<tr>
<td>topsoil plastic limit*</td>
<td>topsoil moisture range: summer</td>
</tr>
<tr>
<td>topsoil liquid limit*</td>
<td>topsoil moisture range: winter</td>
</tr>
<tr>
<td>topsoil liquidity index*</td>
<td>overlap in moisture range: winter/summer</td>
</tr>
<tr>
<td>topsoil thickness*</td>
<td>difference in shear strength: July/February</td>
</tr>
<tr>
<td>topsoil bulk density*</td>
<td>topsoil ratio sand:clay</td>
</tr>
<tr>
<td>topsoil % organic carbon*</td>
<td></td>
</tr>
<tr>
<td>topsoil % sand*</td>
<td></td>
</tr>
<tr>
<td>topsoil % silt*</td>
<td></td>
</tr>
<tr>
<td>topsoil % clay*</td>
<td></td>
</tr>
<tr>
<td>topsoil shear strength (February)</td>
<td></td>
</tr>
<tr>
<td>topsoil shear strength (May)</td>
<td></td>
</tr>
<tr>
<td>topsoil shear strength (July)</td>
<td></td>
</tr>
<tr>
<td>topsoil shear strength (November)</td>
<td></td>
</tr>
</tbody>
</table>

* refer to Table 6.1  
+ refer to Table 6.4  
# refer to Table 6.5
The positional and topographic data can be found in Table 6.1 and a summary of the measured data describing the physical properties can be found in Tables 6.4 and 6.5. The data for the remainder of the measured variables (listed above in Table 7.1) are presented in Table 7.2 and Table 7.3, while Table 7.4 shows the data for the computed descriptors.

Table 7.2 Tree density, effective slope and recorded shear strength for each sample point, with the standard error given in brackets (where appropriate).

<table>
<thead>
<tr>
<th>Point Reference</th>
<th>Trees per m²</th>
<th>Slope along ridges, degrees</th>
<th>Shear strength*(Feb) kPa</th>
<th>Shear strength*(May) kPa</th>
<th>Shear strength*(Jul) kPa</th>
<th>Shear strength*(Nov) kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.035</td>
<td>2.4</td>
<td>25</td>
<td>24</td>
<td>50</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.55)</td>
<td>(0.86)</td>
<td>(0.78)</td>
<td>(0.39)</td>
</tr>
<tr>
<td>A2</td>
<td>0.059</td>
<td>2.9</td>
<td>36</td>
<td>50</td>
<td>100</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.59)</td>
<td>(1.11)</td>
<td>(1.63)</td>
<td>(0.30)</td>
</tr>
<tr>
<td>A9</td>
<td>0.041</td>
<td>2.2</td>
<td>25</td>
<td>28</td>
<td>56</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.57)</td>
<td>(0.89)</td>
<td>(1.12)</td>
<td>(0.61)</td>
</tr>
<tr>
<td>A10</td>
<td>0.064</td>
<td>2.7</td>
<td>34</td>
<td>42</td>
<td>72</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.76)</td>
<td>(1.46)</td>
<td>(1.73)</td>
<td>(0.61)</td>
</tr>
<tr>
<td>B5</td>
<td>0.030</td>
<td>6.3</td>
<td>23</td>
<td>36</td>
<td>84</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.53)</td>
<td>(0.75)</td>
<td>(1.33)</td>
<td>(0.37)</td>
</tr>
<tr>
<td>B6</td>
<td>0.173</td>
<td>4.0</td>
<td>30</td>
<td>37</td>
<td>116</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.45)</td>
<td>(0.65)</td>
<td>(0.73)</td>
<td>(0.61)</td>
</tr>
<tr>
<td>B7</td>
<td>0.039</td>
<td>5.3</td>
<td>25</td>
<td>33</td>
<td>69</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.34)</td>
<td>(0.61)</td>
<td>(1.49)</td>
<td>(0.36)</td>
</tr>
<tr>
<td>B8</td>
<td>0.165</td>
<td>4.7</td>
<td>40</td>
<td>44</td>
<td>102</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.64)</td>
<td>(0.97)</td>
<td>(1.31)</td>
<td>(0.57)</td>
</tr>
<tr>
<td>C3</td>
<td>0.040</td>
<td>0.6</td>
<td>25</td>
<td>25</td>
<td>66</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.63)</td>
<td>(0.89)</td>
<td>(1.70)</td>
<td>(0.32)</td>
</tr>
<tr>
<td>C4</td>
<td>0.113</td>
<td>1.6</td>
<td>38</td>
<td>40</td>
<td>72</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.62)</td>
<td>(0.69)</td>
<td>(1.39)</td>
<td>(0.72)</td>
</tr>
<tr>
<td>C11</td>
<td>0.155</td>
<td>2.2</td>
<td>44</td>
<td>46</td>
<td>86</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1.17)</td>
<td>(0.69)</td>
<td>(1.00)</td>
<td>(0.66)</td>
</tr>
<tr>
<td>C12</td>
<td>0.116</td>
<td>2.9</td>
<td>33</td>
<td>36</td>
<td>70</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.88)</td>
<td>(0.63)</td>
<td>(1.04)</td>
<td>(0.43)</td>
</tr>
</tbody>
</table>

* the slope of the ground orthogonal to the surface contour

** these data are represented in graphical format in Figure 6.11

As a first exploration of any inter-relation between these variables, a Pearson correlation matrix was derived (Table 7.5). Where the correlation is found to be significant at the 0.01 level, the correlation coefficient is shown in red, while values in blue indicate significance at the 0.05 level. A 2-tailed significance test has been employed as interest, at this stage, is in purely the strength of the correlation between variables, regardless of the direction of that correlation.
Table 7.3 Summary of mean volumetric topsoil moisture data (m$^3$ m$^{-3}$) collected during 2001.

<table>
<thead>
<tr>
<th>Point Reference</th>
<th>Jan</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Aug</th>
<th>Sep</th>
<th>Sep</th>
<th>Oct</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.437</td>
<td>0.427</td>
<td>0.438</td>
<td>0.451</td>
<td>0.438</td>
<td>0.409</td>
<td>0.340</td>
<td>0.304</td>
<td>0.335</td>
<td>0.262</td>
<td>0.339</td>
<td>0.256</td>
<td>0.286</td>
<td>0.411</td>
<td>0.379</td>
<td>0.446</td>
<td>0.434</td>
</tr>
<tr>
<td>A2</td>
<td>0.378</td>
<td>0.366</td>
<td>0.379</td>
<td>0.414</td>
<td>0.408</td>
<td>0.355</td>
<td>0.268</td>
<td>0.214</td>
<td>0.220</td>
<td>0.207</td>
<td>0.265</td>
<td>0.206</td>
<td>0.256</td>
<td>0.381</td>
<td>0.336</td>
<td>0.394</td>
<td>0.382</td>
</tr>
<tr>
<td>A9</td>
<td>0.440</td>
<td>0.427</td>
<td>0.441</td>
<td>0.446</td>
<td>0.447</td>
<td>0.392</td>
<td>0.350</td>
<td>0.316</td>
<td>0.319</td>
<td>0.254</td>
<td>0.333</td>
<td>0.228</td>
<td>0.293</td>
<td>0.391</td>
<td>0.378</td>
<td>0.448</td>
<td>0.420</td>
</tr>
<tr>
<td>A10</td>
<td>0.391</td>
<td>0.390</td>
<td>0.389</td>
<td>0.410</td>
<td>0.408</td>
<td>0.377</td>
<td>0.269</td>
<td>0.215</td>
<td>0.225</td>
<td>0.221</td>
<td>0.291</td>
<td>0.206</td>
<td>0.248</td>
<td>0.371</td>
<td>0.333</td>
<td>0.396</td>
<td>0.393</td>
</tr>
<tr>
<td>B5</td>
<td>0.449</td>
<td>0.429</td>
<td>0.449</td>
<td>0.466</td>
<td>0.442</td>
<td>0.392</td>
<td>0.330</td>
<td>0.296</td>
<td>0.320</td>
<td>0.264</td>
<td>0.337</td>
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Table 7.4. Physical data computed for the topsoil at each sample point.

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<thead>
<tr>
<th>Site Ref.</th>
<th>Trees per m²</th>
<th>Moisture range* (m³ m⁻³)</th>
<th>Winter range* (m³ m⁻³)</th>
<th>Summer range* (m³ m⁻³)</th>
<th>Range overlap (m³ m⁻³)</th>
<th>Moisture modal value** (m³ m⁻³)</th>
<th>Winter modal value** (m³ m⁻³)</th>
<th>Summer modal value** (m³ m⁻³)</th>
<th>ratio sand: clay</th>
<th>Shear strength difference Jul:Feb (kPa)</th>
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<td>0.195</td>
<td>0.072</td>
<td>0.155</td>
<td>0.032</td>
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<td>0.43</td>
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<td>0.726</td>
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<td>0.45</td>
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<td>0.144</td>
<td>0.067</td>
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<td>0.38</td>
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</table>

* The winter period is defined as January-mid May and October-December (see §7.2.1.1)

** The modal value (rounded to 2 decimal places) is the most frequently occurring (raw) soil moisture measurement recorded during the given time frame
### Table 7.5. Correlation matrix for the physical soil properties.

<table>
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<tr>
<th>trees/m²</th>
<th>slope</th>
<th>plastic limit</th>
<th>liquid limit</th>
<th>liquidity index</th>
<th>bulk density</th>
<th>Organic C</th>
<th>% sand</th>
<th>% silt</th>
<th>% clay</th>
<th>slope Feb</th>
<th>slope May</th>
<th>slope Jul</th>
<th>shear Feb</th>
<th>shear May</th>
<th>shear Jul</th>
<th>shear Nov</th>
<th>moisture mode</th>
<th>moisture mode</th>
<th>summer mode</th>
<th>winter mode</th>
<th>moisture range</th>
<th>range overlap</th>
<th>shear Jul/Fe</th>
<th>ratio sand:clay</th>
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<td>0.01</td>
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<td>0.25</td>
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<td>0.82</td>
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<td>0.49</td>
<td>0.69</td>
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<td>0.93</td>
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</table>

The table provides the correlation coefficients between various physical soil properties, including trees/m², slope, aspect, plastic limit, liquid limit, liquidity index, bulk density, Organic C, % sand, % silt, % clay, slope Feb, slope May, slope Jul, shear Feb, shear May, shear Jul, shear Nov, moisture mode, moisture mode, summer mode, winter mode, moisture range, range overlap, shear Jul/Fe, and ratio sand:clay.
Soil samples were analysed for 10 variables describing the chemical properties of the topsoil (Table 7.6). A determination of the pH of the soil was made on two occasions: once in early May when the topsoil was coming towards the end of a prolonged wet period, and again in September following summer drying. This allowed for any changes in pH between the start and end of a growing season, due to changes in soil nutrient status during the intervening months, to be noted. A summary of these chemical data can be found in Table 6.4 while the matrix of Pearson correlation coefficients is shown in Table 7.7. As before, values in red indicate significance at the 0.01 level while values in blue indicate significance at the 0.05 level.

Table 7.6. Measured soil chemical characteristics.

<table>
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<th>Measured parameters</th>
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<td>pH (May 2001)</td>
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<tr>
<td>pH (September 2001)</td>
</tr>
<tr>
<td>conductivity</td>
</tr>
<tr>
<td>nitrate N (NO₃⁻)</td>
</tr>
<tr>
<td>ammonia N (NH₄⁺)</td>
</tr>
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<td>extractable phosphate</td>
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<tr>
<td>extractable aluminium</td>
</tr>
<tr>
<td>extractable calcium</td>
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</table>

A study of the correlation matrices allows an exploration of the potential for using certain (easily measured) soil descriptors as indicative of soil conditions which are more costly or time-consuming to measure directly. Assuming such pedotransfer functions can be identified (with a high level of confidence) then it should be possible to model key soil attributes over a wider area based on easily obtained empirical data.
Table 7.7. Correlation matrix for the chemical soil properties.

<table>
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<th></th>
<th>trees/m²</th>
<th>pH (May)</th>
<th>pH (September)</th>
<th>conductivity</th>
<th>nitrate</th>
<th>ammonia</th>
<th>phosphate</th>
<th>potassium</th>
<th>magnesium</th>
<th>aluminium</th>
<th>calcium</th>
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</thead>
<tbody>
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</tr>
<tr>
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</tr>
<tr>
<td>pH (September)</td>
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</tr>
<tr>
<td>conductivity</td>
<td>-0.29</td>
<td>0.46</td>
<td>0.37</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>nitrate</td>
<td>-0.37</td>
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<td>0.29</td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>ammonia</td>
<td>-0.07</td>
<td>0.01</td>
<td>-0.15</td>
<td>0.60</td>
<td>0.34</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>phosphate</td>
<td>0.05</td>
<td>0.25</td>
<td>0.14</td>
<td>0.08</td>
<td>-0.02</td>
<td>0.14</td>
<td>1.00</td>
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<tr>
<td>potassium</td>
<td>-0.87</td>
<td>0.71</td>
<td>0.69</td>
<td>0.28</td>
<td>0.60</td>
<td>0.25</td>
<td>-0.22</td>
<td>1.00</td>
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<tr>
<td>magnesium</td>
<td>-0.66</td>
<td>0.68</td>
<td>0.73</td>
<td>0.35</td>
<td>0.37</td>
<td>-0.27</td>
<td>-0.27</td>
<td>0.63</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>aluminium</td>
<td>0.88</td>
<td>-0.86</td>
<td>-0.90</td>
<td>-0.32</td>
<td>-0.30</td>
<td>0.18</td>
<td>0.08</td>
<td>-0.70</td>
<td>-0.85</td>
<td>1.00</td>
<td></td>
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<td>calcium</td>
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<td>0.81</td>
<td>0.82</td>
<td>0.60</td>
<td>0.31</td>
<td>0.23</td>
<td>0.10</td>
<td>0.67</td>
<td>0.61</td>
<td>-0.83</td>
<td>1.00</td>
</tr>
</tbody>
</table>
The experimental design for this research (§6.1) detailed an exploration of the patterns of tree success in relation to topographic factors. A brief glance at the correlation matrix (Table 7.5) shows no significant correlation between the tree density and the slope of the ground (Pearson correlation coefficient \( r = 0.29 \)); between the tree density and the slope along the drainage ridges \( r = 0.01 \); or between the tree density and the aspect, or direction, of slope \( r = 0.25 \). It would be reasonable to assume that in an area of such gentle slopes (between two and seven degrees) and with little change in altitude (100 to 120 metres MSL), that the landscape position would not be a dominant factor in determining the success or failure of tree planting.

The correlation matrix (Table 7.5) does, however, indicate a number of soil parameters that correlate significantly with tree density. The correlation between tree density and topsoil shear strength (particularly during the winter months, \( r = 0.85 \) for November); tree density and bulk density \( r = -0.73 \); and tree density and winter topsoil moisture patterns \( r = 0.87 \) for winter range and \( r = -0.71 \) for winter modal value) are all significant at the 0.01 level. Correlation coefficients significant at the 0.05 level are found between tree density and topsoil thickness \( r = 0.67 \); and tree density and the annual topsoil moisture patterns \( r = 0.64 \) for annual range and \( r = -0.69 \) for the annual modal value).

The correlation matrix (Table 7.7) of the chemical soil variables indicate the relations between tree density and pH \( r = -0.85 \) in May), exchangeable potassium \( r = -0.87 \), aluminium \( r = 0.88 \) and calcium \( r = -0.79 \) as being significant at the 0.01 level. The relation between tree density and exchangeable magnesium \( r = -0.66 \) is significant at the 0.05 level.

The remainder of this chapter seeks to explore these relationships between tree density and the (significant) physical and chemical soil properties in order to determine their role in explaining the differential success of tree planting across the study area.
7.2.1 Spatial patterns and cross-correlation of physical variables

An initial exploration was carried out to describe the patterns and ranges of values found for each of the measured variables, at each of the sample points. The objective was to determine if any clear spatial patterns existed in the data. The twelve sampling points were chosen to cover a range of topographic and vegetation conditions across the study site, as described in §6.2.4. Until empirical evidence was collected from the field it was impossible to ascertain whether the soils at each of the points showed any differences in terms of their physical or chemical structure, and, if so, whether those differences could be related to patterns of successful tree establishment.

7.2.1.1 Spatial variation in topsoil moisture patterns

Volumetric soil moisture data were collected for each point as described in §6.3. A summary of the mean volumetric soil moisture recorded at each point for each date is shown in Table 7.3. This table shows that, throughout the entire sampling period, both winter and summer, and within each region (A, B and C), the points with lower tree density values were consistently wetter than the points with higher tree densities. This is more easily seen in graphical format as shown in Figure 7.1a where the mean recorded volumetric soil moisture values for the points within region A are shown (along with the rainfall for the site) for each of the sampling dates. It can clearly be seen from the upper graph that point A1 (with low tree density) remains wetter throughout the year than point A2. The lower graph shows a similar pattern with point A9 (low tree density) consistently recording higher soil moisture values than point A10. A similar pattern can be observed in the data from region B (Figure 7.1b) and from region C (Figure 7.1c) where all four points have been plotted on a single graph to show that the point with the lowest tree density (C3) is consistently wetter than all other sampling points in this region. Mean volumetric soil moisture readings for the topsoil for the four points within region A range from a minimum of 0.206 m$^3$ m$^{-3}$ (points A2 and A10 in August) to 0.451 m$^3$ m$^{-3}$ (point A1 in March).
Figure 7.1a Daily rainfall and mean volumetric soil moisture for the sampling points within region A, 2001.
Figure 7.1b Daily rainfall and mean volumetric soil moisture for the sampling points within region B, 2001.
Figure 7.1c Daily rainfall and mean volumetric soil moisture for the sampling points within region C, 2001 (lower diagram indicates relative position of each point along slope).
The points within region B show values of between 0.119 m³ m⁻³ (point B8 in June) and 0.466 m³ m⁻³ (point B5 in March). Region C values ranged from 0.120 m³ m⁻³ (point C12 in June) to 0.455 m³ m⁻³ (point C3 in October).

In order to gain an understanding as to how the soil moisture patterns varied across the twelve sampling points, a number of derived variables were computed from the raw field data. These derived variables are shown on the right hand side of Table 7.1 and include the range in volumetric soil moisture content for the entire year and for the summer (mid-May to end-September) and winter (January to mid-May and October to December) periods and the modal soil moisture value recorded for these periods. The data are presented as part of Table 7.4. The variables describing the range of values (for the summer period, the winter period and the full year) have been determined using the mean value recorded at each point and on each sampling date, while the variables describing the modal values are based on all of the field readings obtained (63 readings per sample point on each sampling date).

The winter and summer periods were defined so as to be mutually exclusive (in terms of dates) and were designed as a simple means of dividing the collected data into convenient subsets. Rather than basing the start and end dates of the 'summer' period on an arbitrary decision, an exploration was made of the patterns evident within the raw data. The graphs in Figure 7.1 clearly show the slope of the transition in soil moisture between values recorded on 9th May 2001 and those recorded on 30th May 2001. For the twelve sampling points the volumetric soil moisture dropped by an average of more than 28% between these dates. This was the first time within the sampling period that the mean change for the twelve sampling points exceeded 20% and so it was decided to include the later date (30th May) in the 'summer' period and the earlier date (9th May) within the 'winter' (or wet) portion of the year. The graphs also show, at the end of the summer, that although the transition back to field capacity was more gradual, by the time sampling occurred in early October, soil moisture values were approaching levels recorded during the winter months and were, on
average, 29% higher than the values recorded in September. It was decided, therefore, to include all of the data for September within the 'summer' period, while the data from October onwards would form part of the 'winter' data set. The moisture range for the summer period for each sampling point was therefore based on the lowest and the highest soil moisture values recorded on all sampling dates between (and including) 30th May 2001 and 26 September 2001, while the moisture range for the winter period was based on readings obtained from all other sampling dates.

The table of Pearson correlation coefficients (Table 7.5) shows a strong positive correlation between the winter moisture range and tree density of 0.87, and a strong negative correlation between the modal winter moisture value and tree density of -0.71 (both significant at the 0.01 level). Tree density is also correlated, at the 0.05 level, with annual moisture range (0.64), with annual modal moisture value (-0.69) and with summer modal value (-0.63). Figure 7.2 shows a scatter graph of winter moisture range against tree density. The linear regression line fitted through these data gives an $R^2$ of 0.76.

![Figure 7.2 Tree density on winter moisture range](image)
Similar patterns can be observed for these derived soil moisture variables as were evident from the raw field data: it is significant that those points with low tree density values experience the lowest range in winter soil moisture values. In order to explore this further the winter modal soil moisture value was plotted against the winter range in soil moisture as shown in Figure 7.3. Good conditions for tree growth, with little development of anaerobic conditions, could be expected where the modal soil moisture value was low (the lower left quadrant of Figure 7.3). If a broad range in soil moisture was recorded over the winter months, alongside a low modal value, then the likelihood of waterlogging is greatly reduced ('extremely good conditions' in the upper left quadrant of Figure 7.3). Conversely, a high modal soil moisture value, if coupled with a broad range in soil moisture, could provide difficult conditions for tree growth with a reasonably high potential for waterlogging to occur ('bad conditions' in the upper right quadrant). The worst case scenario occurs where the modal soil moisture value is high and there is little range in the soil moisture conditions during the winter months.

![Figure 7.3 Exploring the likelihood for winter waterlogging of the topsoil](image)
Under these circumstances the topsoil is likely to be waterlogged for prolonged periods with a strong possibility for the development of anaerobic conditions. Field observation of the points clustered to the bottom right of Figure 7.3 (A1, A9, A10, C3, B5 and B7) showed them to be waterlogged throughout much of the winter fieldwork season leading to the development of anaerobic conditions and the consequent difficulties for vegetation growth. Changes in moisture pattern in the topsoil can be beneficial in helping to redevelop soil structure which may have been lost due to handling or storage. Bullock et al. (1985) found that there was natural regeneration of porosity in the top five centimetres of soil which had been compacted due to wheeling by agricultural machinery, but that soil at greater depth remained compacted for longer. They found that wetting and drying during the summer months had most effect in this recovery of porosity. Similarly, Blackwell et al. (1985) noted that changes in bulk density extended to at least 30 cm depth after wheeling by agricultural machinery, but found that wetting and drying was instrumental in helping to regain structure to a depth of 15 cm.

Aside from looking at how the soil moisture regime could be affecting the success/failure of tree planting across the study site, the correlation matrix (Table 7.5) highlights a number of interesting cross-correlations between the soil moisture variables and the other physical soil characteristics. As explored earlier, there is a strong correlation between the winter range of volumetric soil moisture values and the range in the shear strength of the soil during these winter months. It is likely that the low shear strengths recorded at this time reflect the waterlogged conditions of the soil and provide little additional insight into the structure and strength of the soil matrix. Similarly, it has already been ascertained that a strong relationship exists between winter shear strength values and bulk density and so it is to be expected that a strong negative correlation (-0.74) would be found between the winter range of soil moisture values and the bulk density recorded for the twelve points with the points of high bulk density (A1, A9, C3 and B5) being those points with a low winter range in soil moisture and showing evidence of prolonged winter waterlogging.
Bulk density is a useful surrogate descriptor of soil structure. As previously discussed, there is a strong relationship between bulk density and the level of success in establishing trees, so it follows that data regarding the spatial variation in bulk density could assist in the targeting of remedial action on failed sites. The determination of bulk density, although not difficult, is time consuming. Value could be added to site investigations if a means could be found whereby bulk density could be predicted based on one, or more, easily collected sets of field observations. The high level of cross correlation between winter shear strength values and winter range of soil moisture means that it would be inappropriate to use both of these factors in any such predictive model. As discussed in §4.6.1, if two highly correlated variables are used in a predictive model, the second variable will add little to the predictive capacity of the model as it is seeking to explain the same variability as the first variable. Given the earlier discussion regarding winter shear strength being indicative of the soil moisture status, it would be more appropriate to design a predictive model for bulk density based on field observations of winter soil moisture conditions. The correlation matrix (Table 7.5) also shows a strong positive correlation between bulk density and the modal moisture values for summer, winter and the full year (0.85, 0.84 and 0.86 respectively), significant at the 0.01 level, again indicating the potential for these easily obtained measures of soil moisture to add weight to a pedotransfer function for bulk density. In order to explore whether these field measurements for soil moisture could be used as a predictor of topsoil bulk density, a range of regression scenarios were explored. The best predictor, based on the available volumetric soil moisture variables, and taking into account any cross-correlation between variables, came from a combination of the summer modal value and winter ranges of soil moisture. The model produced is shown in Figure 7.4, has an $R^2$ value of 0.79 (adjusted $R^2 = 0.74$) and a $p$-statistic of 0.001. This analysis would suggest that the use of soil moisture parameters which describe the moisture status of the soil in both its dry (the summer modal value) and wet (the winter range) states, has potential for the prediction of soil bulk density without the need for costly and time consuming laboratory analysis.
This development of predictive equations compliments other research in the area of pedotransfer functions (Shoulders and Tiarks, 1980; Moore et al., 1993; Hernanz et al., 2000).

7.2.1.2. Spatial variation in topsoil thickness

Topsoil thickness for each of the twelve sample points was determined by using a window of nine grid cells (3 by 3) from the modelled grid of topsoil thickness, centred on the sample point. As each grid cell covered a four metre by four metre square area, this window of nine cells covered a total area of 144 m². The mean value of the nine
cells making up the window was taken as being representative of the local topsoil thickness for that point. The modelling procedure for topsoil thickness is described in §6.3.4 and is discussed further in §7.3.1 below.

Topsoil thickness for the four points within region A ranges from 129 to 191 mm with a mean of 158 mm. The points within region B show values of between 106 and 183 mm with a mean of 142 mm. The greatest thickness of topsoil is to be found for the points within region C with values of between 163 and 203 mm and an average of 188 mm.

Figure 7.5 shows these ranges of topsoil thickness values. It is interesting to note that, although the values differ from region to region, in all three cases the points with the shallowest topsoil have the lowest tree densities. Combining the data for regions A, B and C to explore the study site in a wider context, it can be seen from Table 7.8 that the points which show poor establishment of trees have topsoil thickness ranging from 106 to 163 mm while those with higher tree densities show topsoil thickness of between 164 and 203 mm. It is normal practice to plant restored sites with small tree stock (less than 1.2 metres tall) that has been raised in a protected nursery environment (Moffat and McNeill, 1994). The Forestry Commission guidelines for planting of such trees on restored sites (Wilson, 1985) recommend that a slit or notch be made with a spade and the plant inserted to the same level as it was in the nursery, with care being taken to ensure that stems and branches are not buried nor roots left exposed. In most cases, for these young trees, this will require planting at a depth of between 150 and 250 mm, with topsoil of adequate thickness and aeration being essential to facilitate root development and plant stability (Moffat and McNeill, 1994).
Table 7.8. Topsoil thickness, based on a 3x3 window of cells extracted from modelled topsoil grid.

<table>
<thead>
<tr>
<th>Point Ref.</th>
<th>Trees per m²</th>
<th>Topsoil thickness mm</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.035</td>
<td>129</td>
<td>0.1</td>
</tr>
<tr>
<td>A2</td>
<td>0.059</td>
<td>173</td>
<td>3.0</td>
</tr>
<tr>
<td>A9</td>
<td>0.041</td>
<td>137</td>
<td>0.9</td>
</tr>
<tr>
<td>A10</td>
<td>0.064</td>
<td>191</td>
<td>1.0</td>
</tr>
<tr>
<td>B5</td>
<td>0.030</td>
<td>106</td>
<td>3.5</td>
</tr>
<tr>
<td>B6</td>
<td>0.173</td>
<td>183</td>
<td>0.4</td>
</tr>
<tr>
<td>B7</td>
<td>0.039</td>
<td>114</td>
<td>1.0</td>
</tr>
<tr>
<td>B8</td>
<td>0.165</td>
<td>164</td>
<td>1.5</td>
</tr>
<tr>
<td>C3</td>
<td>0.040</td>
<td>163</td>
<td>2.0</td>
</tr>
<tr>
<td>C4</td>
<td>0.113</td>
<td>188</td>
<td>1.7</td>
</tr>
<tr>
<td>C11</td>
<td>0.155</td>
<td>199</td>
<td>0.4</td>
</tr>
<tr>
<td>C12</td>
<td>0.116</td>
<td>203</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The Pearson correlation coefficient between topsoil thickness and tree density is 0.67 and is significant at the 0.05 level (Table 7.5) which, in conjunction with the Forestry Commission guidelines discussed above, indicates that topsoil thickness may be a significant factor in explaining the spatial patterns of tree success across the site. Research has been carried out on various issues associated with topsoil thickness and its contribution to the successful restoration of disturbed land to forestry (Andrews et al., 1999; Bending et al., 1999; Bending and Moffat, 1999; Binns, 1983). In many cases forestry is the planned after-use precisely because topsoil stocks are limited and a return to agricultural use would not be feasible. In some restoration programmes, such as Bramshill Forest in Hampshire, tree planting occurred even though no topsoil replacement had taken place (Binns, 1983). Although it could be expected that limitation to growth would be evident, due to low fertility and nutritional problems, Binns (1983) found that many trees grew quite well on subsoils alone, although the lack of organic matter in the subsoil layer was found to lead to nitrogen deficiency, and nitrogen fixing species (such as alder) were recommended for such sites. In relation to the study site under investigation for this research, soil thickness was such that, at
many points (in particular A1, A9, B5 and B7, see Table 7.8) most root stock would have been laid below the topsoil horizon. The thickness of the topsoil can affect the success or failure of tree establishment for a number of reasons. Firstly, the supply of organic material in the topsoil affords a supply of nutrients to the rooting zone of the trees. A greater thickness of topsoil is better able to provide such nutrient supply over a longer time span. Secondly, the topsoil layer acts as a buffer mechanism for supplying water to the tree root zone. A greater thickness of topsoil allows a more controlled percolation of precipitation through the profile to the rooting zone and less runoff to the drainage channels. Thirdly, the structure of the topsoil is noticeably less compact that that of the subsoil layer (based on a visual inspection of several soil faces from pits excavated across the study site). A greater thickness of topsoil will afford a greater availability of soil air, and a greater protection against waterlogging and the development of anaerobic conditions.

When the site was restored, the planting density of the tree stock was planned to be consistent across the site. The use of the ‘trees per m$^2$’ variable, as detailed above, is designed to provide a crude indication of the extent to which this consistency has been achieved. Figure 7.6 shows a scatter graph of tree density against topsoil thickness with the positive relationship being evident. A linear regression line fitted through these data gives an $R^2$ of 0.46, while the fitting of an exponential curve (as shown) increases the $R^2$ value to 0.61. A number of sample points show greater residuals from the regression line, in particular points B6 and B8, both of which fall in areas of successful tree establishment. It is interesting to note that the other points of successful tree establishment show a much closer fit to the exponential curve. The low level of residuals associated with the points having less topsoil, may indicate the presence of a threshold level for the topsoil thickness variable, possibly in the order of 160 mm, below which topsoil may limit successful tree establishment. In order to explore this relationship further, the data for the modelled grids of topsoil depth and tree density were analysed.
The data were summarised to give an average topsoil depth for each tree density band (from 0.01 to 0.19 trees per m\(^2\) with an interval of 0.01). The analysis showed that the average topsoil thickness was 160 mm in areas where tree density was 0.04 trees per m\(^2\) and rose to 183 mm in areas where tree density exceeded 0.18 trees per m\(^2\). Figure 7.7 shows the mean topsoil thickness against tree density for the modelled areas (shown in Figure 6.16). Fitting an exponential curve (as for the original twelve sampling points above) gives an R\(^2\) value of 0.74. As these are mean values for each tree density band it is inappropriate to explore the residuals from the curve, as any outliers will have been 'smoothed' by the averaging process. Given that the data presented here are representative of a greater geographical extent than that of the twelve sampling points, the analysis adds considerable weight to the contention that topsoil thickness is an important factor in supporting successful tree establishment.
Figure 7.7 Tree density on modelled topsoil thickness, with exponential regression curve fitted.

A shallow topsoil layer could be contributing to detrimental soil moisture conditions by promoting winter waterlogging and summer desiccation of the soil, or by limiting the supply of available plant nutrients. Referring back to the graph of tree density on topsoil thickness (Figure 7.6) it would seem that a topsoil thickness in excess of 150-160 mm is required to achieve tree establishment at densities above the required density of 0.04 trees per m².

It is impossible to know, some 8 years after restoration, whether a consistent thickness of topsoil was applied across the full extent of the restored site, although the restoration details presented as part of the planning application indicate that to have been the intention. Engineers specify restoration depths in millimetres which would indicate a level of accuracy that is difficult to achieve in practice (Reeve et al., 2000). Topsoil thickness measured across the study site ranged from 91 - 231 mm (Table 7.9) and correlated strongly with elevation (Pearson correlation coefficient of 0.70, \( p=0.01 \)).
Table 7.9 Summary statistics for field sampled topsoil thickness cores.

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>Count (points)</th>
<th>Mean (mm)</th>
<th>Maximum (mm)</th>
<th>Minimum (mm)</th>
<th>Range (mm)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>35</td>
<td>165</td>
<td>201</td>
<td>129</td>
<td>72</td>
<td>24</td>
<td>4.1</td>
</tr>
<tr>
<td>B</td>
<td>63</td>
<td>156</td>
<td>192</td>
<td>91</td>
<td>101</td>
<td>28</td>
<td>3.5</td>
</tr>
<tr>
<td>C</td>
<td>29</td>
<td>190</td>
<td>231</td>
<td>148</td>
<td>83</td>
<td>17</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Topsoil replacement would have been carried out at restoration time using box-scrapers and bulldozers with the intention of replacing a minimum topsoil layer across the site. The nature of these operations are such that it is difficult to achieve consistent results. Slope of land and direction of working are both factors likely to cause variation in the performance of the grader. The amount of trafficking on any given area, subsequent to the spread of topsoil, can affect both the topsoil thickness and the soil bulk density, due to increased compaction of the soil structure. Even when soils have been loosened, the beneficial impacts (reduced bulk density, reduced shear strength) have been shown to be lost within three years and the settling of dilate soils has been found, over the period of just one winter, to lower a soil surface by several centimetres (Twomlow et al., 1994). Before concluding that topsoil thickness variation is solely due to differences in grader performance at the time of restoration, it is necessary to explore the likelihood of a number of other possible explanations.

Brubaker et al. (1993) found increased yield on footslopes within their study area which they attributed to the deposition of soil, organic matter and nutrients which had been eroded from upslope positions. They also found that lower positions had more available water than did the higher positions. The patterns found at this study site coincide with their research in terms of the availability of water at foot slope positions, but this research found shallower topsoil horizons in the lower lying positions (Figure 6.16). It would seem, therefore, that the imposed system of drainage ridges leads to a
different pattern of water, soil and nutrient movement than would be found on an area of 'natural' topography. The lower positions across the study regions tended to have shallower topsoil horizons and, being on gentler slopes, were more prone to waterlogging than the higher positions. Field observations across the study region showed that, within these lower lying areas, the furrows created along the planting lines (in order to raise small planting ridges) were much less pronounced that those observed on higher positions. This characteristic was most pronounced in the area in the eastern part of the study region where the planting ridges run almost parallel to the direction of slope and promote downslope movement of water and material. There are a number of possible explanations for this smoothing of the planting ridges. It may be that, at the time of restoration, this low lying area either was not furrowed so effectively, perhaps due to its proximity to the main drainage channel and consequent limitations on the movement of apparatus, or, that the area was overworked by machinery after the furrows had been raised due to operations being carried out when restoring the drainage channel. It is also possible that colluvial soil movement has redistributed material from the ridges into the furrows. Regardless of the reason, this effective removal of the furrows in areas of very low slope, coupled with the shallowness of the topsoil layer, could be important factors in explaining the patterns of prolonged winter waterlogging observed in these areas.

This waterlogging, in turn, will impact on the nutrient status of the soil. Many valuable plant nutrients are lost from the system either through leaching, denitrification or chemical reduction. Other ions (such as iron and manganese) can reduce into readily soluble forms and then be taken up by the vegetation in toxic quantities (Andrews et al., 1998). The development of anaerobic conditions can cause structural decomposition of the plant root membranes causing less effective uptake of water and ions. By inhibiting the breakdown of organic material, anaerobicity can slow soil-forming processes in these areas (Brady, 1990).
Field observations, made on site visits, have shown that waterlogging of the topsoil is a regular occurrence and, in certain areas of the site, is often prolonged, especially during the winter months. Observed patterns of waterlogging appear to be related to topsoil thickness (as discussed above) and to the directionality of the imposed drainage in relation to the slope of the land surface. These two factors affect the efficiency with which surface water, and possibly topsoil and plant nutrients, may be removed to the main drainage channels and into the lakes. A calculation was made for each of the twelve sample points to determine the difference in orientation between the local slope of the land and the direction of the imposed drainage ridges (henceforth called DIRDIFF, for DIRection DIFFerence). A DIRDIFF of 0° will occur in areas where the ridge and furrow landforms follow the downslope direction of the land surface, thereby suggesting a degree of efficiency in moving surface water from the slope. As DIRDIFF values tend towards 90° the ploughed ridges tend to coincide with the local contour and offer no assistance to surface water movement. Indeed, at 90° the rills impede runoff and cause ponding of water (Hudson, 1971). The covariation between topsoil thickness and DIRDIFF is shown in Figure 7.8 with the R² value of 0.37.

Figure 7.8 Topsoil thickness against slope difference DIRDIFF (landform/ridges).
This covariation, and consideration of a number of other factors found at the site, indicate that colluvial soil movement is unlikely to be contributing to the spatial difference in topsoil thickness across the study site. Topsoil thickness data used in the statistical analysis were obtained from locations on the top of the ploughed ridges but the imposed system of ridges and furrows would tend to concentrate soil loss in the furrows and so any such loss would not be reflected in the measurements obtained. The degree of slope found across the study site ranged from 0 - 9 degrees and so the gravitational stresses influencing both surface water flow and particulate mass movement will be low. Surface runoff will therefore be predominantly of low velocity. The soils themselves were found to contain between 30 and 45% clay (Table 6.5) and therefore to be of low erodibility. These factors combine to indicate that soil erosion is unlikely to have been a major factor effecting any change in topsoil thickness during the time between restoration and the undertaking of this research. Another possible factor to explain the difference in topsoil thickness is that some areas were subjected to increased trafficking by machinery, leading to further compaction of the replaced top soil and higher bulk density values. If this were the case then one would expect to find a negative relationship between topsoil thickness and topsoil bulk density, with bulk density being higher where the topsoil has been compressed into a shallower layer. Figure 7.9 shows the plot of bulk density and topsoil thickness for the twelve sampling points.

![Figure 7.9 Topsoil thickness on bulk density](image)
The relationship is negative, and Table 7.5 shows that the Pearson correlation coefficient between these two variables is -0.69 \((p=0.05)\). Given that, for reasons discussed above, soil erosion is unlikely to have been a dominant process across the site, this relationship between bulk density and soil thickness is unlikely to have been brought about by removal of a substantial layer of less compact topsoil.

Considering the evidence obtained from the site - the use of heavy and imprecise machinery in the restoration procedures; the strong correlation between topsoil thickness and elevation; the low erosion potential due to low gradient slopes and soil material of low erodibility; and the relationship between soil thickness and bulk density - it seems likely that the observed variation in topsoil thickness can largely be explained by the working of the site at the time of restoration. There is unlikely to have been an even spread of topsoil across the site. This raises important issues for future restorations, as data obtained from the study site show topsoil thickness to be an important factor in determining the level of success of tree planting. If restoration to forestry is to succeed, a minimum level of topsoil needs to be available across the extent of the restored site, not to provide a rooting medium for the planted stock but rather to provide an adequate nutrient supply and to control the supply of moisture to the rooting zone.

7.2.1.3 Spatial variation in topsoil bulk density

Soil structure refers to the manner in which individual particles are held together to form aggregates, or peds, within the soil. The space between the soil particles or soil peds will affect the way in which water and air move through the soil. Good drainage depends on the free movement of water through the pore space of a reasonably open soil structure as, once it has entered the soil profile, water drains through the natural fissures in the soil (McDougall, 1998). Cemented or compacted horizons lead to difficulties for root penetration and also cause problems as the reduced potential for deep seepage can lead to a tendency to waterlogging (McDougall, 1998). Bulk density,
although time-consuming and expensive to obtain, is often regarded as the most useful
descriptor of soil structure, and, as it is directly related to soil porosity, can be used as
an indicator of soil compaction or loosening (Hernanz et al., 2000). Data were
collected to explore the variation in topsoil bulk density across the study site. Bulk
density measurements were obtained via the core method (Blake and Hartage, 1986) as
detailed in Chapter 6. Other variables were measured to provide additional information
about the physical properties of the soil: these include soil shear strength; particle size
distribution; percentage of organic matter and the Atterberg values for plastic and
liquid limits. These data are presented in Table 7.10.

Bulk density measurements for the four sampling points within region A range from
1.31 to 1.44 Mg m\(^{-3}\), the mean value for these points being 1.37 Mg m\(^{-3}\). Of these four
points, A2 and A10 show lower bulk density values while A1 and A9 have higher
values, indicating higher levels of soil compaction at the areas where tree growth is
poorest. The points within region B show bulk density values of between 1.28 and 1.45
Mg m\(^{-3}\) with a mean of 1.35 Mg m\(^{-3}\). Again the points with higher bulk density (B5 and
B7) are the points of lower tree density. Region C produced bulk density values
ranging from 1.29 to 1.44 Mg m\(^{-3}\) with a mean of 1.33 Mg m\(^{-3}\). Of these four points,
there was little variation in bulk density between points C4, C11 and C12, while C3,
the point with the fewest trees, was noticeably higher, with a value of 1.44 Mg m\(^{-3}\).

The measured values for bulk density across the twelve sampling points ranged from
1.28 to 1.45 Mg m\(^{-3}\). These values compare favourably with values of 1.54 Mg m\(^{-3}\)
recorded by Bending et al. (1991) for a restored site in South Wales and of 1.53 Mg m\(^{-3}\)
recorded by Bussler et al. (1984) for a site in southwest Indiana. The values recorded
in this study are of similar magnitude to values recorded by Antonopoulos and
Wyseure (1998) where they found bulk densities of 1.49 Mg m\(^{-3}\) for a restored site at
Acklington in the north east of England.
Bulk density measurements were obtained for two control points using the same procedures as employed at the twelve sample points. Again, five cores were taken and the bulk density determined for the core section from two to ten centimetres depth in the topsoil horizon. These control points were located in a region of mature woodland, bordering onto the area of restored land, and can be identified by the red markers to the bottom right of the photograph enclosed as Appendix 1. These soils had a pronounced fresh organic litter horizon overlying a mixed organo-mineral layer to a depth in excess of 200 mm. Field investigation, and subsequent particle size analysis, identified soils of a clay-loam texture indicating the likelihood of Ticknall series soils as described in §5.5. The topsoil bulk density values returned for these soils were 1.23 and 1.26 Mg m$^{-3}$. These values are comparable to bulk densities of 1.29 Mg m$^{-3}$ recorded by Antonopoulos and Wyseure (1998) and by Davies et al. (1992) for undisturbed soils, although they are higher than the typical value of 1.10 Mg m$^{-3}$ reported by Juma (2001) for clay loam soils.

Table 7.10. Mean topsoil bulk density, based on 5 cores per sample point.

<table>
<thead>
<tr>
<th>Point Ref.</th>
<th>Trees per m$^2$</th>
<th>Mean bulk density Mg m$^{-3}$</th>
<th>Standard error of mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.035</td>
<td>1.41</td>
<td>0.02</td>
</tr>
<tr>
<td>A2</td>
<td>0.059</td>
<td>1.31</td>
<td>0.01</td>
</tr>
<tr>
<td>A9</td>
<td>0.041</td>
<td>1.44</td>
<td>0.03</td>
</tr>
<tr>
<td>A10</td>
<td>0.064</td>
<td>1.32</td>
<td>0.04</td>
</tr>
<tr>
<td>B5</td>
<td>0.030</td>
<td>1.45</td>
<td>0.02</td>
</tr>
<tr>
<td>B6</td>
<td>0.173</td>
<td>1.33</td>
<td>0.03</td>
</tr>
<tr>
<td>B7</td>
<td>0.039</td>
<td>1.34</td>
<td>0.01</td>
</tr>
<tr>
<td>B8</td>
<td>0.165</td>
<td>1.28</td>
<td>0.02</td>
</tr>
<tr>
<td>C3</td>
<td>0.040</td>
<td>1.44</td>
<td>0.01</td>
</tr>
<tr>
<td>C4</td>
<td>0.113</td>
<td>1.29</td>
<td>0.04</td>
</tr>
<tr>
<td>C11</td>
<td>0.155</td>
<td>1.29</td>
<td>0.01</td>
</tr>
<tr>
<td>C12</td>
<td>0.116</td>
<td>1.31</td>
<td>0.01</td>
</tr>
<tr>
<td>control1</td>
<td></td>
<td>1.23</td>
<td>0.01</td>
</tr>
<tr>
<td>control2</td>
<td></td>
<td>1.26</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Figure 7.10 shows a scatter graph of tree density against topsoil bulk density and highlights the negative relationship between the variables. The fitted (second order polynomial) trend line gives an $R^2$ of 0.54. Root growth, and therefore the potential for successful establishment of trees, is reduced in compacted soils (Dobson and Moffat, 1993). Heilman (1981) found root penetration of Douglas fir seedlings to decline linearly with soil bulk densities ranging from 1.37 to 1.77 Mg m$^{-3}$ and ceasing altogether at bulk densities of 1.74 to 1.83 Mg m$^{-3}$. Again it is interesting to note that, as for the relation between topsoil thickness and tree density (Figure 7.6), there are a number of sampling points, this time with the lower bulk density values, which are outlying from the regression line. For this model, the outlying sample points are A2, A10, B6 and B7. Of these four points, only B7 is designated as having poor tree growth, although the tree density values for points A2 and A10 are lower than those for the successful points within regions B and C. Of these four points, A10 and B6 were also outliers on the model linking tree density to topsoil thickness.

These data, and the fitted trend line, indicate a reduction in tree density as bulk density increases to a value in the order of 1.35 Mg m$^{-3}$ beyond which tree density becomes asymptotic. This value is somewhat lower than the 1.6 Mg m$^{-3}$ found by Brady (1990).
to constrain root growth and, although bulk density is not a property for which a requirement can easily be specified during the restoration process, a value of 1.35 Mg m\(^{-3}\) is lower than the 1.50 Mg m\(^{-3}\) currently recommended to promote surface rooting within restored soils (Bending et al., 1999). Zisa et al. (1980) found the growth of Austrian pine roots on a silt loam to be severely restricted at a bulk density of 1.40 Mg m\(^{-3}\) while on a sandy loam soil a similar restriction of root growth was noted at bulk density of 1.80 Mg m\(^{-3}\). Bowen (1981) found a similar relationship between soil texture and the bulk density at which root penetration ceased with heavier soils restricting penetration at lower bulk densities than lighter soils. Given that changes in bulk density directly influence soil permeability, surface drainage, and trafficability as well as root penetration, there is scope for additional research to be carried out in order to determine whether the current guidelines for the bulk density of restored soils are in need of revision. This research indicates that soil bulk densities of 1.35 Mg m\(^{-3}\) (and above) are found in areas of poor tree success and offers support to the conclusions of Moffat and Bending (2000) that the poor performance of many planting schemes on restored sites may be due to a failure to address the issues of soil compaction.

The Pearson correlation matrix (Table 7.5) shows that the winter range in volumetric soil moisture content has a negative correlation (at the 0.01 level) with bulk density, while the modal volumetric soil moisture content correlates positively (at the 0.01 level) with bulk density. This means that, in the areas of high bulk density, once the soils have reached saturation point they are slow to drain and remain in a very wet (often near-saturated) condition for prolonged periods. This, in turn, leads to all of the potential problems (as discussed in Chapter 3) associated with the development of anaerobic conditions. The areas of lower topsoil bulk density experience repeated cycles of wetting and drying throughout the year, with the soil responding much more rapidly to changes in weather conditions. Repeated wetting and drying of topsoil has been found to aid in the recovery of porosity and structure within restored soils (Blackwell et al., 1985; Bullock et al., 1985) and will be discussed further in later sections.
7.2.1.4 Spatial variation in topsoil shear strength

Shear strength data were collected at a depth of six centimetres using the procedures detailed in Chapter 6. Shear strength data were collected in tandem with measurements of volumetric soil moisture. Data for each of the twelve sampling points were collected on four sampling dates throughout 2001 (19 February, 9 May, 30 July and 21 November). These sampling dates were selected in order to give information for a range of conditions of topsoil moisture: from maximum soil wetness in February, through the start of the drying phase in early May, and conditions at the height of summer, to a re-wetting phase in November. Unfortunately, rainfall in the spring of 2001 was high, with 82 mm falling in March and 115 mm falling in April, compared with a mean of 51 mm for March and 73 mm for April in the previous eight years (see Table 6.9). This meant that the moisture and shear strength data, collected during the planned fieldwork campaign in May, returned values similar to those recorded in February. Although this gave less shear strength data for the soils in a dry state, these data confirmed the extent and duration of the near saturated conditions found in the soils across much of the study site. By late July, the topsoil moisture readings recorded at all twelve points were the lowest recorded during the entire sampling period. The topsoil shear strength data collected at this time are therefore representative of the soil in its driest state during the 15 month fieldwork phase of this research. Longer term soil moisture data, measured at a depth of ten centimetres, were available for a sampling station positioned within region B. The minimum summer soil moisture, for this station, for the period 1997-2000 ranged from 0.210 to 0.290 m$^3$ m$^{-3}$. The data collected for this research project were of a similar range as was recorded for this longer time period. The field conditions during the fieldwork phase of this research can, therefore, be taken as being representative of longer term conditions experienced across the study site. A summary of the shear strength data for the twelve points and for each of the sampling dates is presented as part of Table 7.2 and can be seen graphically in Figure 6.11.

Topsoil shear strengths for the four points within region A range from 25 to 36 kPa in February 2001 to between 50 and 100 kPa in July 2001. The mean values for these
points for February, May, July and November are 30, 36, 70 and 31 kPa, respectively. Of these four points, A2 shows the greatest range in shear strength from 36 kPa during the winter months to 100 kPa in July, a range of 64 kPa which equates to a 178% increase from February to July. The points within region B show shear strength values of between 23 and 40 kPa in February 2001 and between 69 and 116 kPa in July 2001. The mean values for these points for February, May, July and November were 30, 38, 93 and 34 kPa, respectively. Region C produced shear strength values of 25 to 44 kPa in February and 66 to 86 kPa in July with means of 28, 37, 74 and 39 kPa for February, May, July and November samples.

As previously noted for soil thickness, it is interesting to see that, although the absolute values differ, in all three regions, and on each sampling date, the points with the lowest topsoil shear strength are those points with the lowest tree density values. Looking at the data for all twelve points, it can be seen from Table 7.2 that the points which show poor establishment of trees have winter shear strength values (using values for February and November) in the order of 20-30 kPa, while those points with higher levels of tree success show winter values of 30 kPa and above. The Pearson correlation coefficients between shear strength and tree density are 0.74 for the February shear values and 0.85 for the November values, both being significant at the 0.01 level (Table 7.5).

As noted in §7.2.1.3 above, a strong negative correlation exists between tree density and bulk density. Given that soil shear strength is usually positively correlated with bulk density it would be expected that a similar negative correlation would be found between shear strength and tree density. The field data recorded, and described above, do not support this supposition, but rather indicate a strong positive correlation. The points where recorded tree density is lowest and where topsoil shear strength is lowest, are the same points where soil bulk density is highest, and where soils are often water logged for prolonged periods. Root growth is greatly reduced when soil conditions are unfavourable due to oxygen reduction, decreased temperature or high levels of
compaction (Dobson and Moffat, 1993). The points showing greater shear strength during the winter months also show a greater range in soil moisture content during this time. This implies that water is able to move through the profile and reduce the likelihood of anaerobic conditions developing with the consequent restriction of root extension. The Pearson correlation coefficients of 0.75 and 0.74 (Table 7.5) show that the topsoil shear strength for the winter months (using the data for February and November, respectively) correlate positively \((p=0.01)\) with the winter range in volumetric soil moisture content. Adding weight to this argument is the fact that, during the winter months, points showing low soil shear strength have high modal soil moisture values. Again, this could be indicative of waterlogged conditions and the development of anaerobic conditions. The Pearson correlation coefficients of \(-0.95\) and \(-0.83\) (Table 7.5) show that the topsoil shear strength for the winter months (using the data for February and November, respectively) correlates negatively (at the 0.01 level) with the winter modal value for volumetric soil moisture content. It is likely that these winter moisture conditions, with the potential for the development of anaerobic conditions, are limiting tree success. The recorded data for soil shear strength during the winter months appear to provide an indication of the moisture conditions within the soil rather than being indicative of any direction relationship between soil shear strength and levels of tree success. Some tree roots can withstand low oxygen levels during the dormant winter period as respiration rates are low, although these same species may react rapidly to adverse conditions if experienced during times of active growth (Yelenosky, 1964). Those areas where soil conditions are such that waterlogging can still be experienced in the early months of spring are therefore susceptible to failure of tree planting. Referring back to Figure 6.22 it can be seen that above average rainfall (based on figures for 1993-2001) was experienced across the study site in the spring (March and April) of 1998 and 1999. Without detailed information regarding the status of the trees for each growth season, it is impossible to state categorically the patterns of tree failure across the study site, however, it is possible that poor soil conditions, coupled with a succession of wet growing seasons, led to some measure of failure of the planted tree stock across the restored site. The ability of some tree species (including willows, poplars and alders) to transport small
quantities of oxygen from the stem to the root system affords some measure of protection against failure, although the survival rate of these trees can be significantly reduced in permanently waterlogged soils (Kozlowski, 1986). Table 5.3 shows that alders were to comprise 15% of the trees to be planted as part of the restoration programme at the study site and yet they formed more than 30% of the trees sampled for this project (Table 6.6) and were in evidence at all but one of the twelve sampling locations. This may, in part, show the benefit to be gained from planting such species in areas prone to restrictive soil conditions.

A positive correlation (Table 7.5) was observed between tree density and the topsoil shear strength recorded in May and July. It is interesting to note that the sampling points with the highest tree densities have higher plastic limits, probably due to their higher percentage of organic matter, than do the points with lower tree densities. The high correlation between tree density and soil shear strength (when the soil is in a dry state) could be due, at least in part, to a greater density of roots affording additional strength to the soil matrix.

7.2.1.5. Spatial variation in other soil physical variables

Having explored the patterns of topsoil moisture, thickness, bulk density and shear strength across the study site, it now remains to explore the physical variables describing soil consistency and particle size analysis, where again some interesting differences can be seen from one sampling region to the next.

7.2.1.5.1. Particle size distribution

The percentage organic carbon and the particle size distribution data are presented in Tables 6.3 and 6.4. These values are based on two replicate analyses for each point, with the soil being selected from five samples that had been bulked and well mixed. The coarse material was removed by wet sieving, while the material of less than 250
microns was analysed by means of a sedigraph following the procedure detailed in
Chapter 3.

The proportion of sand ranges from 18 to 34%, silt from 32 to 43% and clay from 32 to
43% across the entire study site. Little variation exists in the particle size distribution
of the soils drawn from the sample points within region A, although point A1 shows a
slightly higher proportion of sand, and a reduced proportion of clay, than the other
points in this region. The soils sampled in region B have a higher proportion of sand
than is found at regions A and C, and have a lower proportion of clay. Field
observations in region B show clear evidence within the topsoil of the presence of
course sand. Sand was added as a soil-forming material at the time of restoration. It is
possible that some localised incidents during the restoration process have given rise to
an uneven distribution of sand across this part of the study site. The samples collected
for analysis may not be representative of the soils within a wider area and the textural
data for region B need to be treated with caution. In region C the soils show a higher
proportion of silt than was found in the soils from the other two regions. The soils fall
within the clay/clay loam/silty clay loam area of the soil texture triangle with most of
the samples classifying as clay loam (Figure 7.11). The samples classified as clay were
all from region A, while one of the samples from region C fell just inside the silty clay
loam limits.

Samples were taken at the same depth of six centimetres at two points from the nearby
undisturbed soil under mature, broad-leaved deciduous forestry. Particle size analysis
was carried out following the same procedures and returned values of 34% sand, 34%
silt and 32% clay, placing this soil in the clay loam category. This similarity between
the particle size distribution of the restored and the undisturbed soils would imply that
the variance in texture is likely to be insignificant in explaining any differences in bulk
density or shear strength in the soils across the restored site. These findings support
those of Armstrong and Bragg (1984) who also report little difference in particle size
distribution between undisturbed and restored soils in Derbyshire and Durham,
although the soils in their study were predominantly loam/silt loam and silty clay loam. One of the dominant soil types in this area, prior to mineral extraction, was the Stanley series (Chapter 5, §5.5). The texture of the soil samples collected across the restored site is similar to the values reported for soils of this series (Table 5.2) indicating that the topsoil replaced across the site is likely to have been that which was removed and stored while opencast mining was in operation.

The difference in the percentage of organic carbon was more pronounced between the undisturbed and the restored sites. The undisturbed topsoil showed between 13.5 and 17.5% organic carbon while the restored soils ranged from 4.5 to 9.2%. No significant correlation was found between tree density and the percentage of organic carbon at the twelve sample points. A strong positive correlation (0.82) exists between the percentage of organic carbon and the soil plastic limit. This is due to the strong attraction of water to humic material enabling a soil with increased levels of organic material to successfully retain more water before structure is lost and plasticity conditions reached. This will be discussed further in the following section.
7.2.1.5.2. Atterberg limits

A determination was made of the plastic and liquid limits, and the plasticity index, of the topsoil for each of the twelve sample points. These values are based on two replicate experiments for each sample point with the soil being selected from 5 samples which had been bulked and well mixed. The data can be seen in Table 6.5.

The plastic limit (given as a moisture % of dry soil) for the four points within region A ranges from 20 to 26% with a mean of 23%. The liquid limits for this region range from 44 to 57% with a mean of 49%. The sample points within region B show a range in plastic limit from 27 to 30% with a mean of 28%. The liquid limit for this region ranges from 56 to 60% with a mean of 58%. The sample points in region C have values falling between those of the other two areas with plastic limits of between 25 and 27% and a mean of 26%; and liquid limits of 46 to 57% and a mean of 52%. For all three regions, the liquid limit is between 20 and 31% higher than the plastic limit. The results, especially for regions A and C, compare favourably with findings from research carried out by the regional government in Alberta, on soils of a similar texture (Alberta Transportation, 2001). Table 7.11 presents the average data for each of the three research areas and three comparable samples from the study in Alberta.

<table>
<thead>
<tr>
<th>Ref. Id</th>
<th>sand</th>
<th>silt</th>
<th>clay</th>
<th>liquid limit (%)</th>
<th>plastic limit (%)</th>
<th>plasticity index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region A</td>
<td>23</td>
<td>36</td>
<td>41</td>
<td>49</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>Alb_01*</td>
<td>22</td>
<td>35</td>
<td>43</td>
<td>49</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td>Region B</td>
<td>32</td>
<td>34</td>
<td>34</td>
<td>58</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>Alb_02*</td>
<td>31</td>
<td>33</td>
<td>35</td>
<td>38</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Region C</td>
<td>22</td>
<td>41</td>
<td>37</td>
<td>52</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Alb_03*</td>
<td>22</td>
<td>42</td>
<td>36</td>
<td>43</td>
<td>18</td>
<td>25</td>
</tr>
</tbody>
</table>

* figures from Alberta Transportation, 2001
The Atterberg limits for the soils from region B are significantly different than those found on undisturbed sites in Alberta. The Atterberg limits must be interpreted in the light of the textural composition of the soil. As discussed above (§7.2.1.5.1.) the sand content of the soils within region B are higher than those of the other regions. It has proved impossible to ascertain precise details of rates of application of soil forming materials across the study site, and, even were such information available, it is unlikely that it would account for any differential application at a local scale or give any indication of the thoroughness with which it was mixed with the existing soil. Given that the twelve sampling points were located using a combination of both systematic and random selection processes (as described in §6.2.4), it was deemed inappropriate to alter the position of study region B simply because the textural nature of the soil showed evidence of differing soil handling processes than were evident in the other regions. Any analysis involving the textural soil properties for points B5-B8 must be undertaken in conjunction with the field observations regarding this region.

Looking at the data for each pair of sampling points (A1 with A2, A9 with A10, and so on) it can be noted that, in general, the points with low tree density have lower plastic and liquid limits than their corresponding high tree density points. The correlation coefficients between tree density and these variables is not significant being 0.49 for plastic limit, 0.50 for liquid limit and 0.45 for liquidity index. These low correlations, however, do not rule out the usefulness of these variables in potential modelling scenarios as the only other variable with which they are strongly cross-correlated is organic carbon. This means that the Atterberg variables may add strength to regression models without raising any problems of multicollinearity.
7.2.2. Soil moisture characteristic curves

Six sets of topsoil samples, two from each of regions A, B and C were sent for laboratory determination\(^1\) of the soil moisture characteristic curve in order to determine whether differences in soil structure and (possibly) pore-size distribution offered any additional explanation of variation in topsoil moisture patterns not accounted for by the measured parameters discussed above. Figure 7.12 shows the moisture characteristic curve for each of the six sets of samples. The curves for region A are shown in blue, those for region B in red, and those for region C in green. For all regions the results from soils sampled in areas of lower tree density are illustrated using a pecked line while areas of higher tree density are denoted by a solid line. At near saturation there is little separation between the six curves with a 6% difference in water content being recorded between the points. The water content at 0.0 kPa is comparable to the liquid limit determinations as described above (§7.2.1.5.2.). A comparison between the mean liquid limit and the water content at 0.0 kPa for the three regions is shown in Table 7.12. It is also interesting to note from Figure 7.12 that, for all three regions, the points of lower tree density retain their moisture for longer as soil water potential moves from saturation, through field capacity towards wilting point.

Table 7.12 Comparison of average water content at 0.0 kPa and Atterberg liquid limit.

<table>
<thead>
<tr>
<th>Ref. Id</th>
<th>mean liquid limit (%)</th>
<th>water content at 0.0 kPa (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region A</td>
<td>49</td>
<td>52</td>
</tr>
<tr>
<td>Region B</td>
<td>58</td>
<td>52</td>
</tr>
<tr>
<td>Region C</td>
<td>52</td>
<td>54</td>
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</tbody>
</table>

\(^1\) Four replicates of each of the six soil samples were extracted using stainless steel volumetrically calibrated cylinders, 5 cm in diameter and volume of 100 cm\(^3\) and analysed by the Laboratory for Soil and Water, University of Leuven, Belgium. http://www.agr.kuleuven.ac.be
Field capacity will vary depending upon the textural composition of the soil. Water draining from a saturated soil will evacuate the largest pores first and drain progressively from smaller pores over time. A day or two following saturation any such gravitational drainage will have stopped as the soil reaches field capacity. Soil at field capacity will have a matric potential varying from -10 to -30 kPa (Foth, 1990). Cassel & Nielsen (1986) reported values in the order of -5 kPa (1.7 pF) for clay soils to -40 kPa (2.5 pF) for sandy soils. The shape of the moisture curves (Figure 7.12) indicates a field capacity in the order of -2 kPa. At this level, the separation of the soil water-release curves between the extremes of the higher tree density area of region C to the low tree density area of region A is a difference in water content of 10%. The
samples taken from all three regions show the areas of low tree density to have a higher water content at field capacity than the areas of high tree density. The separation, at -2 kPa, between high and low tree density areas for region A is 3.7%, for region B is 4.3% and for region C is 2.7%.

At permanent wilting point (PWP), taken as being -1500 kPa, the separation between the best and the worst points is again a difference in water content of 10%. There is a noticeable convergence in the release curves for the soils from regions A and B with a mean water content of 26% (S.E. 0.38) as the potential moves from field capacity towards wilting point, while the soils from region C return a mean water content of 18%, some 8% lower.

Table 7.13 Available water content, based on FC - PWP.

<table>
<thead>
<tr>
<th>Ref. Id</th>
<th>available water content (%) (-2 to -1500 kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region A: lower tree density</td>
<td>18.55</td>
</tr>
<tr>
<td>Region A: higher tree density</td>
<td>14.09</td>
</tr>
<tr>
<td>Region B: lower tree density</td>
<td>17.71</td>
</tr>
<tr>
<td>Region B: higher tree density</td>
<td>14.62</td>
</tr>
<tr>
<td>Region C: lower tree density</td>
<td>17.30</td>
</tr>
<tr>
<td>Region C: higher tree density</td>
<td>17.00</td>
</tr>
</tbody>
</table>

Table 7.13 shows the available water content for each of the regions. For each of the three regions sampled, the soils from the areas of higher tree density have less available water than those within the areas of lower tree density. These data provide useful verification that, if soil moisture patterns are detrimentally affecting the successful establishment of trees across the study site, it is moisture retention and waterlogging during the winter months, as opposed to drought stress during the summer months, that is imposing any such limitation.
The samples for these moisture release curves were taken, on average 11 metres (S.E. = 1.5 m) from the nearest of the twelve regular sampling points (A1 - C12). Pearson correlation coefficients were determined between the soil moisture content at field capacity and a range of measured parameters as shown in Table 7.14.

Table 7.14 Pearson correlation coefficient between soil moisture (%) at field capacity (-2 kPa) and physical soil properties.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Pearson correlation coefficient</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>bulk density</td>
<td>0.87</td>
<td>0.023</td>
</tr>
<tr>
<td>% silt</td>
<td>-0.93</td>
<td>0.008</td>
</tr>
<tr>
<td>soil shear strength (February)</td>
<td>-0.93</td>
<td>0.008</td>
</tr>
<tr>
<td>soil shear strength (November)</td>
<td>-0.94</td>
<td>0.005</td>
</tr>
<tr>
<td>soil moisture range</td>
<td>-0.77</td>
<td>0.076</td>
</tr>
<tr>
<td>soil moisture modal value</td>
<td>0.90</td>
<td>0.013</td>
</tr>
<tr>
<td>soil moisture mode: summer</td>
<td>0.92</td>
<td>0.010</td>
</tr>
<tr>
<td>soil moisture mode: winter</td>
<td>0.88</td>
<td>0.023</td>
</tr>
<tr>
<td>soil moisture range: winter</td>
<td>-0.90</td>
<td>0.009</td>
</tr>
</tbody>
</table>

The determination of soil moisture characteristic curves is both time consuming and costly, but can produce clear indications of variations in soil structure. The strong correlation coefficients in Table 7.14 indicate the likelihood of any such structural variation having being captured in the measurement and determination of the soil properties listed.

7.2.3 Spatial patterns and cross correlation of chemical variables

The data described to date have been concerned with spatial patterns of physical soil attributes, soil moisture patterns, and their relation to the success or failure of tree planting across the site. Physical properties are not solely responsible for determining
vegetation success. As discussed in Chapter 3, soil chemical conditions have a role to play in exerting some level of control over the success or failure of any planted vegetation. Conditions across the study site are constant in terms of rainfall, temperature and humidity. Soils have been subjected to consistent treatment during restoration in that soils have been replaced to a similar thickness and no fertiliser has been applied (other than around the root bole at the time of planting the tree stock). It is reasonable, therefore, to assume that any variation in chemical conditions is a reflection of the natural spatial heterogeneity of the soil and not a result of any particular activity occurring as a result of the site restoration. This thesis is, therefore, not working from the premise that variations in soil chemistry have been instrumental in producing the observed patterns of success/failure of the tree planting programme. Research is ongoing (Bending et al., 1991; Johnson & Williamson, 1994) into chemical factors affecting tree growth on restored sites, in particular looking at the dynamics of soil nitrogen during and after restoration (Antonopoulos & Wyseure, 1998). For the purposes of this research, it was thought important that a snapshot of the chemical status of the soil be obtained and an exploration made of any spatial patterns of variation in soil chemistry in the light of the contemporary pattern of vegetation across the site. If recommendations are to be made concerning remedial action to be taken at areas where planting has failed, it is necessary to have an understanding of the underlying chemical status of the soil, in order to ensure that deficiencies in these areas can be addressed if necessary. To that end, soils were tested for ten chemical variables as listed in Table 7.6. The procedures used for testing are described in Chapter 3 while a summary of the data can be found in Table 6.4.

Soil samples for chemical analysis were taken from the field in September and analysed immediately. When agricultural soils are analysed prior to the application of fertiliser, such analysis is usually undertaken in the autumn (after harvest) as a treatment to support the following year's growth (Hoskinson et al., 2002). September was therefore chosen as the sampling period in order to provide data concerning levels of soil nutrient availability at the end of an annual growing season. Figure 6.14 provides an indication of the nutrient status of the soil at each of the sampling points in
relation to the range of values found by Bradshaw and Chadwick (1980) to be necessary for healthy plant growth.

7.2.3.1. Spatial variation in soil pH.

Topsoil pH was measured on two occasions from soil samples taken for each of the twelve sample points. On each occasion five topsoil samples were collected from the upper 10 cm of the soil profile at each point. Each sample volume was at least 75 cm$^3$ and all of the samples were air dried and bulked. Five sub-samples were then selected for analysis from this bulked material and three readings taken with the pH meter for each sample. Full details of the procedure employed are given in Chapter 3.

The readings taken in May 2001 for the four sample points within region A range from pH 6.20 to pH 7.02 with a mean of pH 6.49. The sample points within region B range from pH 4.16 to pH 5.97 with a mean of pH 5.11. The soils from the sample points in region C range from pH 4.97 to pH 6.79 with a mean of pH 5.55. Compared with the values recorded in May, the samples analysed in September 2001 for region A cover a narrower range of values with a minimum of pH 6.49, a maximum of pH 6.95, and a mean of pH 6.71. In contrast, the range of pH values for region B is greater than that recorded in May with values ranging from pH 4.52 up to pH 6.45 with a mean of pH 5.53. The samples analysed for region C in September show a range in pH from a minimum of pH 5.73 to a maximum of pH 6.66 and a mean of pH 6.03.

Regardless of the differences in the range of values, for each of the three regions, the mean pH value recorded in September is higher than that recorded in May. The differences in pH values between these sampling epochs is, on average, less than 0.5 of a unit. Minor fluctuations in soil pH can be accounted for by the movement of salts as soil moisture moves through the profile, however because of the logarithmic nature of the pH scale a change of 0.5 units of pH in acid soils can be significant if this results in the mobilisation of (potentially) toxic metals. Reductions in pH can occur during the
growing season (which would be underway during sampling in May) as acids are produced by micro-organisms and plant roots. As temperatures drop, the pH may increase slightly as biotic activity slows (Brady, 1990). Figure 7.13 shows the range of pH values recorded on the two sampling dates.

The overall range of values for pH for the entire site, for both sampling dates, runs from a low of 4.16 to a high of 7.02. Work on similar topsoils in the south Wales coalfield carried out by Bending et al. (1991) found a range of pH from 4.5 to 8.2. Using the descriptions for pH range as given by Sparks (1995) and shown in Table 7.15, all of the points within region A can be described as being slightly acid to neutral and remain so across the sampling periods. The points in region B range from extremely acid (B8) to moderately acid (B5 and B7) in May, but move towards the slightly acid category by September. Within region C, soils range from very strongly acid (C11 and C12) through strongly acid (C4) to slightly acid to neutral (C3) in May,
and decrease in acidity between May and September. Bradshaw and Chadwick (1980) give a pH range of between 5.0 and 7.5 as being the normal range essential for healthy plant growth (refer to Table 3.3).

Table 7.15. Descriptive terms for soil pH ranges (from Sparks, 1995).

<table>
<thead>
<tr>
<th>Description</th>
<th>pH range</th>
</tr>
</thead>
<tbody>
<tr>
<td>extremely acid</td>
<td>&lt; 4.5</td>
</tr>
<tr>
<td>very strongly acid</td>
<td>4.5 - 5.0</td>
</tr>
<tr>
<td>strongly acid</td>
<td>5.1 - 5.5</td>
</tr>
<tr>
<td>moderately acid</td>
<td>5.6 - 6.0</td>
</tr>
<tr>
<td>slightly acid to neutral</td>
<td>6.1 - 7.3</td>
</tr>
<tr>
<td>slightly alkaline</td>
<td>7.4 - 7.8</td>
</tr>
</tbody>
</table>

Three of the twelve sample points fall outside of this range in the May sampling epoch with points B6, B8 and C12 having values of less than pH 5.0. Of these points only B8 is still outside of this 'healthy' range in September. All of these points show reasonable success in tree establishment with B6 and B8 being the two points designated as 'successful' in region B. It would seem therefore that these low pH values are not indicative of conditions that are limiting the successful establishment of trees. At the other end of the pH spectrum, research by Bending et al. (1991) indicates a reduction in micronutrient availability in soils of pH 7.5 and above. None of the points sampled in this research project showed pH values in excess of this limit.

7.2.3.2. Spatial variation in concentrations of calcium, magnesium and potassium

Referring back to Figure 6.14, it can be seen that concentrations of exchangeable calcium, magnesium and potassium across the study site fall within, or exceed, the limits specified for healthy plant growth (Table 3.3). It is therefore unlikely that variation in the supply of these nutrients has contributed to the differential patterns of
tree success evident across the restored site. Similar patterns in the concentrations of these nutrients can be seen across the three sampling regions and the correlation matrix (Table 7.7) indicates a strong negative correlation between these nutrients and tree density.

Recorded concentrations of calcium ranged from 85 to 235 mg 100 gm$^{-1}$. In region A, values range from 145 to 235 mg 100 gm$^{-1}$ with a mean of 205 mg 100 gm$^{-1}$. There is no apparent correlation between tree density and calcium concentrations. In region B however, the points with high tree density show lower levels of calcium in the topsoil. In this region, values range from 85 to 215 mg 100 gm$^{-1}$ with a mean of 140 mg 100 gm$^{-1}$. Similarly, in region C the highest recorded concentration of calcium is for the sample point with the lowest tree density. Calcium concentrations for region C range from 95 to 210 mg 100 gm$^{-1}$ with a mean of 155 mg 100 gm$^{-1}$. Taking the data for the three regions combined, region A has the highest levels of calcium recorded across the study site and is also the region where tree growth has been poorest, with even the 'good' tree sample points reaching densities which are only slightly better than the 'poor' sample points for regions B and C. The correlation coefficient between tree density and calcium concentrations is $-0.79$ ($p=0.01$).

Magnesium, as a major plant nutrient, is involved in photosynthesis processes (Heinrichs and Mayer, 1977). The level required for plant growth (Table 3.3) is given as between 5 and 30 mg 100 gm$^{-1}$ and, as for calcium, all of the sample points fall within, or exceed these levels. The range across the entire site is from 13.0 to 37.1 mg 100 gm$^{-1}$. Concentrations found within region A range from 28.0 to 37.1 mg 100 gm$^{-1}$ with a mean of 33.2 mg 100 gm$^{-1}$; region B ranges from 13.0 to 33.7 mg 100 gm$^{-1}$ and has a mean of 27.5 mg 100 gm$^{-1}$; and region C ranges from 26.6 to 34.5 mg 100 gm$^{-1}$ with a mean of 31.2 mg 100 gm$^{-1}$. Levels of magnesium are generally lower at the points of higher tree density giving a correlation coefficient of $-0.66$ ($p=0.05$). Bending et al. (1991) found a similar negative relationship between magnesium and yield. It is interesting to note that magnesium deficiency is frequently associated with
low pH conditions and that sample point B8 has noticeably lower pH values and lower concentrations of magnesium than any of the other sample points.

Concentrations of potassium recorded across the twelve sample points again fall within the required levels for healthy plant growth (Table 3.3), with the exception of point B8 which is slightly less than the 10.0 mg 100 gm\(^{-1}\) threshold. In region A, values for potassium range from 16.5 to 26.0 mg 100 gm\(^{-1}\) with a mean of 20.8 mg 100 gm\(^{-1}\). The sampling points with low tree density (A1 and A9) show higher levels of potassium than the points with higher tree density. A similar pattern is observed across region B where values range from 9.4 to 27.5 mg 100 gm\(^{-1}\) with a mean of 16.8 mg 100 gm\(^{-1}\), reduced by the very low value found at point B8. The low tree density points (B5 and B7) show higher concentrations of potassium than do the points with better tree establishment. The values for region C range from 10.3 to 21.3 mg 100 gm\(^{-1}\) with a mean of 13.7 mg 100 gm\(^{-1}\). Again the point with the lowest density of trees (C3) has a much higher level of available potassium than do the other three points in this region. The correlation coefficient determined for tree density and potassium concentrations is -0.87 \((p=0.01)\).

When comparing the data from this research with that reported by Scullion and Malinovsky (1995) for the topsoil of two restored opencast sites in South Wales, concentrations of magnesium and calcium are found to be of a similar order, while potassium concentrations are slightly higher. The data would indicate that soil conditions for calcium, magnesium and potassium are adequate to support tree growth. The negative correlation coefficients between tree density and these three nutrients may reflect the fact that the points with few established trees are losing little of the available nutrient pool to uptake by the trees during the active growing season (Marschner, 1995).
7.2.3.3. Spatial variation in concentrations of phosphorus and nitrogen

Referring back to Figure 6.14, it can be seen that concentrations of phosphate across the study site fall within, or exceed, the limits specified for healthy plant growth (Table 3.3) while, for many of the sample points, levels of ammonia and nitrate nitrogen are below these specified levels. Although this could be indicative of potential nitrogen deficiency across the study site, further analysis of the data indicates that some of the sample points reporting low nitrogen concentrations (B6, B8, C4 and C12) are points where vigorous tree growth is evident. The correlation coefficients between tree density and both phosphate and nitrogen concentrations are low and insignificant.

Phosphate is a major plant nutrient, particularly beneficial in stimulating root growth. Concentrations recorded in the topsoil across the study site in September 2001 ranged from 0.5 to 4.4 mg 100 gm\(^{-1}\). No phosphorus fertiliser was added to the study site at the time of restoration. Phosphorus demand by the vegetation must therefore be met by the conversion of organic and inorganic P from the soil into soluble P and made available for plant use. The required range of phosphorus concentrations to support successful plant growth is given in Table 3.3 as between 0.5 and 2.0 mg 100 gm\(^{-1}\). All of the sample points show levels within, or in excess of, this range. The points within region A show values for phosphate ranging from 0.8 to 4.4 mg 100 gm\(^{-1}\) with a mean value of 2.2 mg 100 gm\(^{-1}\). Within region B, levels of phosphate range from 1.1 to 2.2 mg 100 gm\(^{-1}\) with a mean of 1.6 mg 100 gm\(^{-1}\) while across region C values range from 0.5 to 2.9 mg 100 gm\(^{-1}\) with a mean of 1.5 mg 100 gm\(^{-1}\). The correlation with tree density is very low at just 0.05 (Table 7.7) indicating that phosphate concentrations are unlikely to be of importance in controlling the level of success or failure of the planted trees.

Samples for chemical analysis were taken in September at a time of optimal conditions for microbial activity, with soils being wet but not waterlogged, and with soil temperatures still warm from summer conditions. This sampling time was chosen as being indicative of conditions when increased levels of mineral N are made available.
for plant growth. Nitrate levels range from 0.09 to 0.51 mg 100 gm$^{-1}$ over the three sampling regions. No nitrogen fertiliser was added to the study site at the time of restoration (although fertiliser was added to the adjoining area being returned to agriculture). Nitrogen demand must therefore be satisfied through mineralisation of organic matter. The required range for plant growth for both nitrate N and ammonia N is given in Table 3.3 as between 0.2 and 2.0 mg 100 gm$^{-1}$. These values are not specific to restored or artificial soils.

The sample points within region A show values for nitrate N ranging from 0.17 to 0.51 mg 100 gm$^{-1}$ with a mean value of 0.29 mg 100 gm$^{-1}$. It is noticeable that the points with higher tree densities have much lower levels of nitrate N, possibly indicating uptake of N by the vegetation, but also implying that the levels at the poorer points are adequate to support plant growth. Levels of ammonia N for this region range from 0 to 1.31 mg 100 gm$^{-1}$ with only points A1 and A2 showing substantial levels of this nutrient. Within region B, levels of nitrate N range from 0.09 to 0.32 mg 100 gm$^{-1}$ with a mean of 0.18 mg 100 gm$^{-1}$ while ammonia N ranges from 0 to 1.23 mg 100 gm$^{-1}$ with again only two points (B5 and B8) showing values within the recommended range for plant growth. As for region A, those points within this region with the higher tree density values show the lower levels of nitrate N. A similar pattern is not evident for the concentrations of ammonia N. Across region C, nitrate N concentrations range from 0.09 to 0.37 mg 100 gm$^{-1}$ with the highest value in this region being found at point C11, an area of high tree density. Ammonia N ranges from 0 to 0.28 mg 100 gm$^{-1}$ with the highest value being found at point C3: an area where tree establishment has failed. The correlation with tree density is low, with a correlation coefficient of -0.37 for nitrate N and just -0.07 for ammonia N.

Although for some points there would be appear to be an adequate supply of N to support vegetation growth, research by Bending et al. (1991) found severe nitrogen deficiency to be a principal cause of poor response of Japanese larch on restored opencast ground. Total nitrogen levels were found to be similar to those of a range of
temperate soils but it was found to be probable that a large proportion of this nitrogen was derived from carbonaceous material of geological origin (Bending et al., 1991). Aldag and Strzynicz (1980) have shown that utilizable mineral nitrogen can be released from these materials but Bending et al. (1991) suggest that the mineralisation of the material was of little significance to the tree growth. There is also the possibility that nitrate N is being lost through processes of denitrification. Many parts of the study site showed standing surface water until late April with a consequent lack of oxygen in the topsoil horizon. This, coupled with warming soil temperatures, leads to a rapid multiplication of the denitrifying organisms. It is beyond the scope of this research to explore in detail the nitrogen cycle across the restored site although other researchers (Williamson & Johnson, 1990; Bending & Moffat, 1999) undertaking research into the nitrogen dynamics of restored soils provide useful insights into the potentially limiting role of nitrogen in the establishment of trees on restored opencast sites.

7.2.3.4. Aluminium toxicity

High levels of aluminium are known to be toxic to plants under conditions of low pH (Foy, 1984) and so an assessment was made of the concentrations of aluminium at the twelve sample points in order to determine whether any such toxicity could be contributing to the variation in tree success across the study site. As was expected, the points with high aluminium levels were also the points with the lowest pH values returning a Pearson correlation of coefficient between aluminium concentration and pH (in September) of -0.90 \((p=0.01)\). Were aluminium toxicity to be limiting tree growth, it would be expected that a negative relationship could be identified between tree density and aluminium levels, and so the coefficient of 0.88 (Table 7.7) may appear surprising at first.

Across the three sampling regions, aluminium concentrations ranged from 0.03 to 3.66 mg 100 gm\(^{-1}\), with half of the twelve sample points having levels in excess of 0.10 mg 100 gm\(^{-1}\) and four points having levels exceeding 1.50 mg 100 gm\(^{-1}\). Overall, the
lowest concentrations are in region A where levels range from 0.03 to 0.53 mg 100 gm\(^{-1}\) with a mean of 0.22 mg 100 gm\(^{-1}\). Region B shows aluminium levels of between 0.03 and 3.66 mg 100 gm\(^{-1}\) with a mean of 1.59 mg 100 gm\(^{-1}\). There is a pronounced difference between the low levels of aluminium found at the points with low tree density (0.03 and 0.05 mg 100 gm\(^{-1}\)) and the high levels found at the points with higher tree density (2.61 and 3.66 mg 100 gm\(^{-1}\)). Across region C concentrations range from 0.06 to 1.89 mg 100 gm\(^{-1}\) and give a mean of 0.90 mg 100 gm\(^{-1}\), again with the higher levels of aluminium being found at the points with the higher tree density values.

Plants have two main methods of tolerating high soil aluminium or deactivating absorbed aluminium (Asp et al., 1988; Cronan et al. 1990). One method is to exclude aluminium at the root surface by excreting alkaline compounds in order to maintain the local pH of the root surface above 5.0. In order to achieve this, the root surface must absorb more negatively charged anions (nitrate and phosphate) than positively charged cations (calcium, magnesium) but this requires either a very high nitrate supply or an ability to exist on low levels of absorbed cations. In the second method, the plant effectively deactivates the absorbed aluminium by forming organic complexes with the aluminium ions and 'dumping' these compounds in woody tissue and cell walls. With this mechanism the plants are likely to be excreting acid at the root surface thereby lowering the soil pH and maintaining high levels of aluminium in the soil. Given that the highest concentrations of aluminium are found at the points with greatest tree density and lowest pH values it would seem likely that this second mechanism could be in operation. It is beyond the scope of this research to explore the intricacies of the relationships between soil acidity, aluminium concentrations and vegetation success, although much research is on-going in this field (Asp et al. 1988; Cronan et al., 1990). For present purposes, the fact remains that sample points exist where high levels of tree success coincide with relatively high concentrations of aluminium. This could indicate that, although not prohibiting tree growth, the conditions might be such that the successful trees are not achieving their full growth potential.
7.2.4 Further discussion of the raw data

The preceding sections have looked briefly at spatial patterns of a range of soil properties between regions (A, B and C) and between sampling points (1 to 12) across the study site. Levels of plant nutrients do not vary greatly between regions and would appear adequate to support tree growth in all cases. Given the nature of the restoration process, with the systematic placing of soils and soil forming materials, it would be expected that geographical position would not affect the chemistry of the restored soil.

It is widely accepted that soils undergo chemical transformations, particularly in relation to nitrogen losses, when held in storage mounds and on redistribution over the restored site. These changes are to be expected across the entire study site and offer no explanation of the local variation in tree success across the restored site. It seems therefore, that, if local variations are to be taken into account when designing planting schemes, or when determining remedial activity for failed sites, the focus should be on the measurement and modelling of physical soil properties. Strong relationships have been shown to exist between a range of physical properties (bulk density, shear strength, winter moisture range, topsoil thickness) and tree density. These relationships have been based on data collected for twelve sampling points across the study site. The next step, taken on in Chapter 8, is to see how well these relationships hold in a wider areal context.
Chapter 8. The wider areal context

"...before we plough an unfamiliar patch
It is well to be informed about the winds,
About the variations in the sky,
The native traits and habits of the place,
What each locale permits, and what denies."

Virgil (70-19 B.C.), from The Georgics (c. 36-29 B.C.) tr. Smith Palmer Bovie

8.1 Introduction

In order to explore how well the relationships developed using the data from the twelve sample points could be used to predict soil properties across a wider area, a range of additional field data were collected for validation and modelling. A detailed survey of topsoil thickness was carried out for each of the three regions and the sampled points used to generate grids of topsoil thickness for the entire extent of each region. Similarly, a detailed survey of topsoil volumetric soil moisture and topsoil shear strength across each region was carried out on two separate occasions: in mid-September, with the soil still in a very dry state; and in mid-December with the soil at field capacity. Again these data were used to generate grids of topsoil moisture and shear strength across the full extent of each region. Data for the tree density for each of the twelve sampling points were used in conjunction with data derived from the aerial photograph of the site to develop an algorithm for modelling tree density across the entire site. Bulk density was modelled across the site using data available for winter shear strength and topsoil moisture variables.

In order to validate the modelled layers of tree density and bulk density generated using the GIS software, additional field data were collected at random points within the sampling regions A, B and C to describe these variables. Eight points were identified across region A, ten points across region B and seven points locations across region C. The points were located in the field on each visit using a hand held GPS. Tree density measurements were made at each of these points by counting the number of trees falling within a five metre radius of the allocated position and determining a value for trees per m$^2$. Time constraints meant that bulk density sampling could not
take place at all twenty-five points, and so a subset of twelve points was selected with three points being analysed within region A, five within region B and three within region C. For bulk density determination, three cores were taken at each point and the average value taken as being representative for that site. The location of these twenty-five validation points is shown in Figure 8.1 while a summary of the data collected for each point is presented as Table 8.1.

These twenty-five validation points also formed the basis of a small survey of soil moisture patterns during the course of the fieldwork season. Soil moisture data was collected for the twelve main sampling points on 18 occasions during 2001 (Table 7.3). Time constraints meant that more detailed, wider area, surveys of topsoil moisture patterns could not be carried at this frequency. It was decided to carry out a detailed survey of regions A, B and C on two occasions during the year (as described above) and an intermittent survey at the twenty-five validation points on five occasions throughout the year. The dates selected for the intermittent sample were at the end of March, April, May, September and October. These dates were selected to allow determination of the range of values from maximum wetness to maximum dryness across the year. The aim of these intermittent surveys was to establish whether consistent relationships existed between the soil moisture data for these twenty-five validation points and that for the twelve main sampling points. These relationships could then be used to predict soil moisture for these twenty-five points for the remaining thirteen sampling epochs for which data were available for the twelve main sampling points. On each occasion, at each validation point, twelve readings were taken with the Thetaprobe: three upslope along the ridge, three downslope and three readings either side of the ridge. These values were averaged to give a mean volumetric soil moisture content for each point. The data are presented as part of Table 8.1.

Each of these additional field work sessions and the resulting data are discussed in more detail in the following sections.
Figure 8.1 Location of validation sampling points for tree density and topsoil bulk density.
Photograph © Crown copyright. Ordnance Survey.
Table 8.1 Summary of the data collected for the validation sample points.

<table>
<thead>
<tr>
<th>Site Ref.</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>October</th>
<th>Measured 5m tree density trees m²</th>
<th>Measured bulk density Mg m⁻³</th>
<th>Modeled 5m tree density trees m²</th>
<th>Modeled bulk density Mg m⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ax1</td>
<td>0.438</td>
<td>0.422</td>
<td>0.340</td>
<td>0.389</td>
<td>0.439</td>
<td>0.025</td>
<td>1.37</td>
<td>0.058</td>
<td>1.37</td>
</tr>
<tr>
<td>Ax2</td>
<td>0.441</td>
<td>0.439</td>
<td>0.331</td>
<td>0.401</td>
<td>0.440</td>
<td>0.000</td>
<td>0.008</td>
<td>0.000</td>
<td>0.008</td>
</tr>
<tr>
<td>Ax3</td>
<td>0.434</td>
<td>0.417</td>
<td>0.320</td>
<td>0.407</td>
<td>0.421</td>
<td>0.076</td>
<td>0.070</td>
<td>0.038</td>
<td>0.023</td>
</tr>
<tr>
<td>Ax4</td>
<td>0.410</td>
<td>0.414</td>
<td>0.287</td>
<td>0.377</td>
<td>0.401</td>
<td>0.038</td>
<td>0.070</td>
<td>0.002</td>
<td>0.028</td>
</tr>
<tr>
<td>Ax5</td>
<td>0.412</td>
<td>0.406</td>
<td>0.273</td>
<td>0.375</td>
<td>0.391</td>
<td>0.102</td>
<td>0.065</td>
<td>0.038</td>
<td>0.032</td>
</tr>
<tr>
<td>Ax6</td>
<td>0.404</td>
<td>0.413</td>
<td>0.297</td>
<td>0.401</td>
<td>0.408</td>
<td>0.038</td>
<td>0.038</td>
<td>0.032</td>
<td>0.032</td>
</tr>
<tr>
<td>Ax7</td>
<td>0.408</td>
<td>0.411</td>
<td>0.307</td>
<td>0.381</td>
<td>0.387</td>
<td>0.102</td>
<td>0.079</td>
<td>0.127</td>
<td>0.069</td>
</tr>
<tr>
<td>Ax8</td>
<td>0.397</td>
<td>0.415</td>
<td>0.317</td>
<td>0.395</td>
<td>0.379</td>
<td>0.127</td>
<td>0.084</td>
<td>0.127</td>
<td>0.069</td>
</tr>
<tr>
<td>Bx1</td>
<td>0.457</td>
<td>0.451</td>
<td>0.351</td>
<td>0.384</td>
<td>0.451</td>
<td>0.025</td>
<td>0.018</td>
<td>0.025</td>
<td>0.018</td>
</tr>
<tr>
<td>Bx2</td>
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<td>0.444</td>
<td>0.337</td>
<td>0.402</td>
<td>0.449</td>
<td>0.038</td>
<td>0.092</td>
<td>0.038</td>
<td>0.092</td>
</tr>
<tr>
<td>Bx3</td>
<td>0.437</td>
<td>0.422</td>
<td>0.307</td>
<td>0.391</td>
<td>0.422</td>
<td>0.064</td>
<td>0.095</td>
<td>0.127</td>
<td>0.069</td>
</tr>
<tr>
<td>Bx4</td>
<td>0.423</td>
<td>0.387</td>
<td>0.251</td>
<td>0.321</td>
<td>0.388</td>
<td>0.051</td>
<td>0.084</td>
<td>0.127</td>
<td>0.069</td>
</tr>
<tr>
<td>Bx5</td>
<td>0.431</td>
<td>0.418</td>
<td>0.311</td>
<td>0.377</td>
<td>0.419</td>
<td>0.089</td>
<td>0.127</td>
<td>0.127</td>
<td>0.069</td>
</tr>
<tr>
<td>Bx6</td>
<td>0.411</td>
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<td>0.260</td>
<td>0.321</td>
<td>0.398</td>
<td>0.153</td>
<td>0.154</td>
<td>0.153</td>
<td>0.154</td>
</tr>
<tr>
<td>Bx7</td>
<td>0.440</td>
<td>0.421</td>
<td>0.318</td>
<td>0.391</td>
<td>0.437</td>
<td>0.013</td>
<td>0.027</td>
<td>0.144</td>
<td>0.135</td>
</tr>
<tr>
<td>Bx8</td>
<td>0.394</td>
<td>0.399</td>
<td>0.197</td>
<td>0.227</td>
<td>0.331</td>
<td>0.038</td>
<td>0.078</td>
<td>0.166</td>
<td>0.135</td>
</tr>
<tr>
<td>Bx9</td>
<td>0.388</td>
<td>0.401</td>
<td>0.217</td>
<td>0.231</td>
<td>0.327</td>
<td>0.076</td>
<td>0.073</td>
<td>0.166</td>
<td>0.135</td>
</tr>
<tr>
<td>Bx10</td>
<td>0.415</td>
<td>0.387</td>
<td>0.251</td>
<td>0.313</td>
<td>0.402</td>
<td>0.191</td>
<td>1.30</td>
<td>0.166</td>
<td>1.30</td>
</tr>
<tr>
<td>Cx1</td>
<td>0.447</td>
<td>0.439</td>
<td>0.392</td>
<td>0.438</td>
<td>0.449</td>
<td>0.064</td>
<td>0.139</td>
<td>0.061</td>
<td>0.139</td>
</tr>
<tr>
<td>Cx2</td>
<td>0.368</td>
<td>0.433</td>
<td>0.281</td>
<td>0.391</td>
<td>0.407</td>
<td>0.115</td>
<td>0.080</td>
<td>0.139</td>
<td>0.132</td>
</tr>
<tr>
<td>Cx3</td>
<td>0.402</td>
<td>0.431</td>
<td>0.367</td>
<td>0.342</td>
<td>0.375</td>
<td>0.140</td>
<td>0.132</td>
<td>0.139</td>
<td>0.132</td>
</tr>
<tr>
<td>Cx4</td>
<td>0.372</td>
<td>0.421</td>
<td>0.264</td>
<td>0.384</td>
<td>0.397</td>
<td>0.229</td>
<td>0.151</td>
<td>0.151</td>
<td>0.151</td>
</tr>
<tr>
<td>Cx5</td>
<td>0.348</td>
<td>0.382</td>
<td>0.205</td>
<td>0.284</td>
<td>0.297</td>
<td>0.216</td>
<td>0.136</td>
<td>0.151</td>
<td>0.151</td>
</tr>
<tr>
<td>Cx6</td>
<td>0.376</td>
<td>0.402</td>
<td>0.188</td>
<td>0.301</td>
<td>0.322</td>
<td>0.191</td>
<td>0.104</td>
<td>0.191</td>
<td>0.104</td>
</tr>
<tr>
<td>Cx7</td>
<td>0.400</td>
<td>0.418</td>
<td>0.163</td>
<td>0.308</td>
<td>0.351</td>
<td>0.140</td>
<td>0.112</td>
<td>1.29</td>
<td>1.26</td>
</tr>
</tbody>
</table>
8.2 Topsoil thickness across a wider area

Details of the field survey undertaken to obtain the additional data on topsoil thickness can be found in §6.3.4 with Figure 6.15 showing the distribution of the sampling points across the study area. Of the 127 sampling points, 35 points covered region A, 63 points covered region B and the remaining 29 points covered region C. Three sampling cores were taken at each point and the mean value used to provide an estimate of the topsoil thickness for that position. The summary statistics for the mean measured topsoil thickness are given in Table 8.2.

Table 8.2 Summary statistics for field sampled topsoil thickness cores.

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>Count (points)</th>
<th>Mean (mm)</th>
<th>Maximum (mm)</th>
<th>Minimum (mm)</th>
<th>Range (mm)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>35</td>
<td>165</td>
<td>201</td>
<td>129</td>
<td>72</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>63</td>
<td>156</td>
<td>192</td>
<td>91</td>
<td>101</td>
<td>28</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>29</td>
<td>190</td>
<td>231</td>
<td>148</td>
<td>83</td>
<td>17</td>
<td>3</td>
</tr>
</tbody>
</table>

These point samples were used to interpolate grids of mean topsoil thickness for the three areas using a Gaussian kriging algorithm with a maximum lag of 40 m (refer to §6.3.4 for details of the interpolation routine used and Figure 6.16 for maps of the modelled grids). The grid cell size was 4 m by 4 m with region A being 2128 m² and described by 133 grid cells; region B being 3584 m² and comprising 224 cells; and region C being 1728 m² and having 108 cells. The summary statistics for these modelled grids of topsoil thickness are given in Table 8.3.

Taking the field data for these three regions (Table 8.2) it can be seen that region C has the highest mean thickness of topsoil with 190 mm compared to 165 and 156 mm for regions A and B respectively.
Table 8.3 Summary statistics for modelled topsoil thickness grids.

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>Count (grid cells)</th>
<th>Mean (mm)</th>
<th>Maximum (mm)</th>
<th>Minimum (mm)</th>
<th>Range (mm)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>133</td>
<td>165</td>
<td>199</td>
<td>128</td>
<td>71</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>224</td>
<td>156</td>
<td>190</td>
<td>91</td>
<td>99</td>
<td>27</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>108</td>
<td>192</td>
<td>209</td>
<td>159</td>
<td>50</td>
<td>11</td>
<td>1</td>
</tr>
</tbody>
</table>

A comparison between the measured and the modelled data (Table 8.2 and Table 8.3) shows that the mean modelled values for each region are similar; as are the maximum, minimum, and range values for regions A and B. The model for region C has produced higher minimum and lower maximum values than those measured in the field and the standard error is lower than for the other two regions. Looking at the field data, there was only one sampling point where a measured topsoil thickness of 231 mm was recorded, the remainder of points having values of 216 mm or less. This (possibly) anomalous reading will have distorted the descriptive statistics for region C. If a lack of available topsoil is found to be limiting to tree growth across the study site, then it follows that region C will have a greater chance of success in supporting tree growth than the other two regions. An initial study of the aerial photograph of the site would suggest that region C has been more successfully restored to trees than the other two regions (refer to Figure 6.6) although there are parts of region B which would appear to have had similar levels of success as some parts of region C. Figure 8.2 shows the generated grids of topsoil thickness for the three regions with the areas of high tree density (0.15 trees per m² or higher). The correlation between thickness of topsoil and high tree density is evident. The Pearson correlation coefficient between tree density and topsoil thickness for the twelve sample points is 0.67 (Table 7.5). Figure 8.2 indicates the presence of a similarly strong correlation across the wider area. This relationship, and the role of topsoil thickness in supporting the successful establishment of trees, will be explored in more detail in the later sections of this chapter.
8.3 Volumetric soil moisture across a wider area

Details of the field survey undertaken to obtain the additional data on topsoil volumetric soil moisture can be found in §6.3.5 with Figure 6.17 showing the distribution of the sampling points across the study area for the two survey dates (6th September, 2001 and 7th December, 2001) and Figure 6.18 showing the modelled grids of soil moisture. The survey in September comprised 175 sampling points of which 49 were located within region A, 88 in region B and 38 in region C. Of the 161 sampling points in the December survey, 43 points covered region A, 82 points covered region B and the remaining 36 points covered region C.

Three Thetaprobe readings were taken at each point, on each date, and the mean value used to provide an estimate of the topsoil volumetric moisture content for that position. The summary statistics for the mean measured moisture contents are given in Table 8.4.

Table 8.4 Summary statistics for field sampled volumetric soil moisture content.

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>No. of samples</th>
<th>Mean (m$^3$ m$^{-3}$)</th>
<th>Maximum (m$^3$ m$^{-3}$)</th>
<th>Minimum (m$^3$ m$^{-3}$)</th>
<th>Range (m$^3$ m$^{-3}$)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 2001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>49</td>
<td>0.304</td>
<td>0.339</td>
<td>0.262</td>
<td>0.077</td>
<td>0.021</td>
<td>0.003</td>
</tr>
<tr>
<td>B</td>
<td>88</td>
<td>0.277</td>
<td>0.332</td>
<td>0.209</td>
<td>0.123</td>
<td>0.024</td>
<td>0.003</td>
</tr>
<tr>
<td>C</td>
<td>38</td>
<td>0.301</td>
<td>0.348</td>
<td>0.248</td>
<td>0.100</td>
<td>0.028</td>
<td>0.005</td>
</tr>
<tr>
<td>December 2001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>43</td>
<td>0.397</td>
<td>0.431</td>
<td>0.368</td>
<td>0.063</td>
<td>0.019</td>
<td>0.003</td>
</tr>
<tr>
<td>B</td>
<td>82</td>
<td>0.412</td>
<td>0.456</td>
<td>0.372</td>
<td>0.084</td>
<td>0.018</td>
<td>0.002</td>
</tr>
<tr>
<td>C</td>
<td>36</td>
<td>0.383</td>
<td>0.408</td>
<td>0.350</td>
<td>0.058</td>
<td>0.014</td>
<td>0.002</td>
</tr>
</tbody>
</table>
These point samples were used to interpolate grids of mean volumetric soil moisture content for the topsoil for the three regions using an exponential kriging algorithm, with a maximum lag of 50 m (refer to §6.3.5 for details of the interpolation routine used and Figure 6.18 for maps of the modelled grids). The grid cell size was 4 m by 4 m with each area having the same dimensions as described for the topsoil thickness model in the preceding section. The summary statistics for these modelled grids of topsoil moisture content are given in Table 8.5.

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>No. of samples</th>
<th>Mean (m$^3$ m$^{-3}$)</th>
<th>Maximum (m$^3$ m$^{-3}$)</th>
<th>Minimum (m$^3$ m$^{-3}$)</th>
<th>Range (m$^3$ m$^{-3}$)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>133</td>
<td>0.304</td>
<td>0.333</td>
<td>0.268</td>
<td>0.065</td>
<td>0.019</td>
<td>0.002</td>
</tr>
<tr>
<td>B</td>
<td>224</td>
<td>0.279</td>
<td>0.332</td>
<td>0.246</td>
<td>0.086</td>
<td>0.016</td>
<td>0.001</td>
</tr>
<tr>
<td>C</td>
<td>108</td>
<td>0.300</td>
<td>0.337</td>
<td>0.277</td>
<td>0.060</td>
<td>0.016</td>
<td>0.002</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>No. of samples</th>
<th>Mean (m$^3$ m$^{-3}$)</th>
<th>Maximum (m$^3$ m$^{-3}$)</th>
<th>Minimum (m$^3$ m$^{-3}$)</th>
<th>Range (m$^3$ m$^{-3}$)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>133</td>
<td>0.397</td>
<td>0.436</td>
<td>0.367</td>
<td>0.069</td>
<td>0.019</td>
<td>0.002</td>
</tr>
<tr>
<td>B</td>
<td>224</td>
<td>0.413</td>
<td>0.452</td>
<td>0.391</td>
<td>0.061</td>
<td>0.012</td>
<td>0.001</td>
</tr>
<tr>
<td>C</td>
<td>108</td>
<td>0.384</td>
<td>0.408</td>
<td>0.360</td>
<td>0.048</td>
<td>0.012</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Taking the field data for these three regions (Table 8.4) it can be seen that region B has the lowest mean soil moisture value in September (0.277 m$^3$ m$^{-3}$) and the highest value in December (at 0.412 m$^3$ m$^{-3}$). The range of values from September minimum to December maximum for region B is 0.247 m$^3$ m$^{-3}$ compared to 0.169 m$^3$ m$^{-3}$ for region A and 0.160 m$^3$ m$^{-3}$ for region C.
Figure 8.2 Areas of high tree density in relation to topsoil thickness.
The broad range in soil moisture across region B indicates efficient drainage of the topsoil. This will lead to improved soil aeration and soil structure and the potential for more successful establishment of trees. Data collected throughout the year for sampling points B5 - B8 (and illustrated in Figure 6.10) confirm this pattern of efficient drainage as the graphs show clear cycles of wetting/drying within the region and illustrate the broad range in moisture values recorded.

A comparison between the measured and the modelled data (Table 8.4 and Table 8.5) shows that the mean modelled values for each region, for each date, are similar to the field measured values. This indicates that an adequate spread of points was used to generate the grids. It is interesting to note that the modelled values for both September and December for regions B and C have produced higher minimum values than those measured in the field although the standard error is lower for the modelled than for the field observed data. The use of kriging as an interpolation method ensures that all data points (within the specified lag distance) contribute to the modelled grid thereby tempering the impact of (possibly) anomalous points: in this case, the low minimum values in the measured data set being smoothed out during the interpolation process.

Soil moisture data for twenty-five validation points were collected on five occasions throughout the year and compared with the data for the twelve main sampling points (A1-C12) that had been collected on eighteen occasions. The data were analysed in order to determine whether moisture values for the twenty-five validation points for the 'missing' thirteen sampling dates could be predicted from the data for the main sampling points. When attempting to model moisture patterns for the validation points in region A only the data from the main sampling points in that region were used (points A1, A2, A9 and A10). Similarly for validation points in region B only main sample points B5, B6, B7 and B8 were used in the model and for region C samples C3, C4, C11 and C12. Although data were only available for five sampling dates, the model regression lines gave a high degree of fit with the adjusted $R^2$ always exceeding 0.90, and the worst case $p$-statistic being just 0.04. The set of regression equations
used to predict soil moisture at the validation points is presented in Table 8.6 with the corresponding $R^2$ and $p$-statistic values. These equations were used to predict topsoil moisture levels for these points for remaining periods in the sampling year. Data for annual, summer and winter moisture range and modal values were determined from a combination of the predicted and the field measured data.

As no meteorological variables are included, these equations provide utility only for the study area and for the time period of the field work. Their purpose is solely to provide a means of estimating topsoil moisture characteristics across a wider area than that sampled for points A1-C12.

Summer modal moisture value was found to be a significant factor in the model for predicting topsoil bulk density (described in §7.2.1.1). In order to predict bulk density across a wider area it would be beneficial to have a grid of values for the summer modal moisture value. Again an exploration of the data for the twelve main sampling points was undertaken and a model for summer modal moisture value developed, based on the topsoil thickness and the topographic variables of degree of slope along the drainage ridges and the direction of slope (or aspect) of the land surface. The regression model gave an $R^2$ value of 0.82 (adjusted $R^2$ 0.76) and a $p$-statistic of 0.0023.

The regression line took the form:

$$\text{predicted summer modal moisture (m}^3 \text{ m}^{-3}) = 0.646 - 0.0489 \text{ slope along ridges (degrees)} + 0.0004 \text{ aspect (bearing)} - 0.0019 \text{ topsoil thickness (mm)}$$

Data from the topographic survey (§6.2.2) had provided grids of values describing aspect and slope along drainage ridges. Empirical data had been used to interpolate a grid of topsoil thickness (§6.3.4). Using these grids, the GIS software was used to implement the equation described above to generate an additional grid of values.
describing the summer modal soil moisture across regions A, B and C. Values were extracted from this grid for the twenty-five validation points and the twelve regular sampling points, and were compared with summer modal soil moisture values based on the field data (for points A1 to C12) and the data derived using the equations in Table 8.6 (for the twenty-five validation points). Figure 8.3 shows a scatter graph of these two data sets with the x-axis showing values based on field data, and the y-axis showing values extracted from the grid. The Pearson correlation coefficient for the two data sets is 0.76 ($p=0.0001$). Given that the grid of summer modal soil moisture makes an important contribution to later modelling, it is reassuring to know that the modelled grid correlates so strongly with the empirical data.

![Figure 8.3 Summer modal soil moisture derived by two methods](image)

* values based on raw data and equations in Table 8.6
** values extracted from derived slope, aspect and thickness grids
The inclusion of the 1:1 ratio line in Figure 8.3 illustrates that the grid-based model (shown on the ordinate) is under-predicting the summer modal soil moisture values. It has already been established that drought stress in summer is not a factor limiting to tree growth across the study site (§7.2.2). This under-prediction at lower soil moistures is unlikely to significantly affect the later modelling of tree growth potential. An under-prediction at higher soil moistures could be significant if modelling the winter modal value as areas prone to waterlogging may be wrongly allocated to a drier category. However, in relation to the summer soil moisture patterns (as in Figure 8.3), an under-prediction of 15-20% generates modelled moisture values of an order suitable to support tree growth.

Table 8.6 Soil moisture model equations for the validations points, based on data from original sample points.

<table>
<thead>
<tr>
<th>Point Ref.</th>
<th>Equation for modelling volumetric soil moisture</th>
<th>Adjusted $R^2$</th>
<th>p-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ax1</td>
<td>$-0.0596 + 1.609 A1 - 0.553 A2$</td>
<td>1.00</td>
<td>0.0018</td>
</tr>
<tr>
<td>Ax2</td>
<td>$0.0497 + 0.424 A9 + 0.497 A10$</td>
<td>0.99</td>
<td>0.0029</td>
</tr>
<tr>
<td>Ax3</td>
<td>$0.0079 + 1.563 A1 - 0.625 A9$</td>
<td>0.99</td>
<td>0.0039</td>
</tr>
<tr>
<td>Ax4</td>
<td>$0.0391 + 0.048 A9 + 0.860 A10$</td>
<td>1.00</td>
<td>0.0015</td>
</tr>
<tr>
<td>Ax5</td>
<td>$0.0019 + 0.121 A1 + 0.855 A2$</td>
<td>1.00</td>
<td>0.0013</td>
</tr>
<tr>
<td>Ax6</td>
<td>$0.1573 + 1.156 A10 - 0.484 A9$</td>
<td>0.95</td>
<td>0.0253</td>
</tr>
<tr>
<td>Ax7</td>
<td>$0.2096 + 1.249 A10 - 0.704 A1$</td>
<td>0.99</td>
<td>0.0045</td>
</tr>
<tr>
<td>Ax8</td>
<td>$0.3374 + 1.661 A2 + 0.441 A9 - 1.823 A1$</td>
<td>0.99</td>
<td>0.0676</td>
</tr>
<tr>
<td>Bx1</td>
<td>$0.2435 + 0.875 B6 - 0.315 B5$</td>
<td>0.97</td>
<td>0.0127</td>
</tr>
<tr>
<td>Bx2</td>
<td>$0.0523 + 0.320 B7 + 0.570 B5$</td>
<td>1.00</td>
<td>0.0006</td>
</tr>
<tr>
<td>Bx3</td>
<td>$0.0092 + 0.563 B5 + 0.384 B7$</td>
<td>0.96</td>
<td>0.0218</td>
</tr>
<tr>
<td>Bx4</td>
<td>$0.0026 + 0.760 B6 + 0.202 B5$</td>
<td>0.99</td>
<td>0.0072</td>
</tr>
<tr>
<td>Bx5</td>
<td>$0.0239 + 0.621 B5 + 0.273 B7$</td>
<td>0.99</td>
<td>0.0032</td>
</tr>
<tr>
<td>Bx6</td>
<td>$0.0071 + 1.245 B6 - 0.306 B8$</td>
<td>1.00</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Bx7</td>
<td>$-0.0502 + 1.406 B5 - 0.390 B6$</td>
<td>0.99</td>
<td>0.0040</td>
</tr>
<tr>
<td>Bx8</td>
<td>$0.4773 + 3.935 B6 - 3.702 B5$</td>
<td>0.99</td>
<td>0.0037</td>
</tr>
<tr>
<td>Bx9</td>
<td>$0.5890 + 4.105 B6 - 4.104 B5$</td>
<td>0.99</td>
<td>0.0055</td>
</tr>
<tr>
<td>Bx10</td>
<td>$-0.0074 + 1.193 B6 - 0.195 B8$</td>
<td>1.00</td>
<td>0.0013</td>
</tr>
<tr>
<td>Cx1</td>
<td>$0.4149 + 0.558 C12 - 0.543 C11$</td>
<td>0.98</td>
<td>0.0121</td>
</tr>
<tr>
<td>Cx2</td>
<td>$0.2097 + 2.261 C11 - 1.641 C4$</td>
<td>0.99</td>
<td>0.0075</td>
</tr>
<tr>
<td>Cx3</td>
<td>$0.6557 + 0.689 C11 - 1.095 C3$</td>
<td>0.93</td>
<td>0.0369</td>
</tr>
<tr>
<td>Cx4</td>
<td>$0.2231 + 0.446 C12 + 1.307 C11 - 1.256 C4$</td>
<td>1.00</td>
<td>0.0026</td>
</tr>
<tr>
<td>Cx5</td>
<td>$0.0277 + 0.925 C11 - 0.015 C4$</td>
<td>0.99</td>
<td>0.0029</td>
</tr>
<tr>
<td>Cx6</td>
<td>$-0.2270 + 0.930 C11 - 0.598 C3$</td>
<td>0.99</td>
<td>0.0030</td>
</tr>
<tr>
<td>Cx7</td>
<td>$0.0618 + 0.971 C12 - 0.118 C3$</td>
<td>1.00</td>
<td>0.0013</td>
</tr>
</tbody>
</table>
Winter moisture range was found to have a strong correlation with tree density (Table 7.5) and was likely to be a significant variable in any model developed to predict tree growth potential. Soil moisture patterns are affected by a variety of physical and topographic factors (as discussed in Chapter 7) and so the winter moisture range may provide a useful surrogate measure of other, physiologically significant, factors. A generated grid of values for the winter range in soil moisture for each of the three regions would, therefore, prove useful in building a predictive model. Exploration of the data for the twelve main sampling points showed the potential for predicting the winter moisture range, based on slope of ground and winter shear strength. This regression model gave an $R^2$ value of 0.79 (adjusted $R^2$ 0.75) and a $p$-statistic of 0.0009. The regression line took the form:

\[
\text{predicted winter moisture range (m}^3\text{ m}^{-3}) = -0.0678 + 0.0036 \text{ winter shear (kPa)} + 0.0129 \text{ slope (degrees)}
\]

Using grids of slope (§6.2.2) and shear strength (§6.3.5), the GIS software was used to implement the equation described above to generate an additional grid of values describing the winter range in soil moisture across regions A, B and C. As for the summer modal moisture values, the relevant data were extracted from this grid for the twenty-five validation points and the twelve regular sampling points, and compared with the winter range in soil moisture based on the field data for these points. Figure 8.4 shows a scatter graph of these two data sets with the x-axis showing values based on field data, and the y-axis showing values extracted from the grid. The Pearson correlation coefficient for the two data sets is 0.60 ($p=0.0001$).

As with the summer modal moisture values, the grid of winter range in soil moisture makes an important contribution in later modelling, and again this validation process highlights a strong correlation between modelled and measured values. These grids of summer and winter soil moisture conditions are further discussed later in this chapter when their role in modelling topsoil bulk density and tree growth potential is explored.
Figure 8.4 Winter range in soil moisture derived by two methods
* values based on raw data and equations in Table 8.6
** values extracted from derived slope, aspect and thickness grids

8.4 Topsoil shear strength across a wider area

Details of the field survey undertaken to obtain the additional data on topsoil shear strength can be found in §6.3.5 with Figure 6.17 showing the distribution of the sampling points across the study area for the two survey dates and Figure 6.19 showing the modelled grids of soil shear strength. The sampling points for the shear strength survey corresponded with those used for the soil moisture survey (§8.3) as the surveys were carried out concurrently. Three readings were taken with the hand shear vane at each sample point, on each date, and the mean value used to provide an estimate of the topsoil shear strength for that position.
The shear vane was forced into the soil, with minimal sideways movement, to a depth of approximately 60 mm. The summary statistics for the mean measured shear strengths are given in Table 8.7.

These point samples were used to interpolate grids of mean shear strength for the topsoil for the three regions using an exponential kriging algorithm, with a maximum lag of 40 m (refer to §6.3.5 for details of the interpolation routine used and Figure 6.19 for maps of the modelled grids). The grid cell size was 4m x 4m with each area having the same dimensions as was used for the topsoil thickness and soil moisture models described above. The summary statistics for these modelled grids of topsoil shear strength are given in Table 8.8.

Table 8.7 Summary statistics for field sampled topsoil shear strength.

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>No. of samples</th>
<th>Mean (kPa)</th>
<th>Maximum (kPa)</th>
<th>Minimum (kPa)</th>
<th>Range (kPa)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>49</td>
<td>123</td>
<td>127</td>
<td>120</td>
<td>7</td>
<td>2</td>
<td>0.29</td>
</tr>
<tr>
<td>B</td>
<td>88</td>
<td>124</td>
<td>128</td>
<td>120</td>
<td>8</td>
<td>2</td>
<td>0.21</td>
</tr>
<tr>
<td>C</td>
<td>38</td>
<td>124</td>
<td>128</td>
<td>119</td>
<td>9</td>
<td>2</td>
<td>0.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>No. of samples</th>
<th>Mean (kPa)</th>
<th>Maximum (kPa)</th>
<th>Minimum (kPa)</th>
<th>Range (kPa)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>43</td>
<td>30</td>
<td>39</td>
<td>24</td>
<td>15</td>
<td>4</td>
<td>0.61</td>
</tr>
<tr>
<td>B</td>
<td>82</td>
<td>27</td>
<td>36</td>
<td>19</td>
<td>17</td>
<td>4</td>
<td>0.44</td>
</tr>
<tr>
<td>C</td>
<td>36</td>
<td>32</td>
<td>39</td>
<td>27</td>
<td>12</td>
<td>3</td>
<td>0.50</td>
</tr>
</tbody>
</table>
Looking firstly at the measured field data (Table 8.7) the expected variation between wet and dry conditions can be observed with the shear strength values in December being much reduced relative to those recorded in September. The mean values for the three regions are similar indicating that, at the extremes of soil wetting/drying, the soils across the entire site behave in a similar fashion. Each region has its poorer points, prone to waterlogging and wetter than surrounding areas; and each region has points which drain freely, are waterlogged for shorter time periods and have better soil structure. It is variation in soil properties at a more local scale that must be causing the differences in the patterns of tree establishment.

As for the soil moisture survey, a comparison between the measured and the modelled data (Table 8.7 and Table 8.8) shows that the mean modelled value for each region equates to the field measured value and indicates that an adequate spread of points was used to generate the grids.

Table 8.8 Summary statistics for modelled topsoil shear strength.

### September 2001

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>No. of samples</th>
<th>Mean (kPa)</th>
<th>Maximum (kPa)</th>
<th>Minimum (kPa)</th>
<th>Range (kPa)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>133</td>
<td>123</td>
<td>125</td>
<td>121</td>
<td>4</td>
<td>0.70</td>
<td>0.06</td>
</tr>
<tr>
<td>B</td>
<td>224</td>
<td>124</td>
<td>128</td>
<td>123</td>
<td>5</td>
<td>0.60</td>
<td>0.04</td>
</tr>
<tr>
<td>C</td>
<td>108</td>
<td>124</td>
<td>125</td>
<td>123</td>
<td>2</td>
<td>0.42</td>
<td>0.04</td>
</tr>
</tbody>
</table>

### December 2001

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>No. of samples</th>
<th>Mean (kPa)</th>
<th>Maximum (kPa)</th>
<th>Minimum (kPa)</th>
<th>Range (kPa)</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>133</td>
<td>30</td>
<td>37</td>
<td>25</td>
<td>12</td>
<td>3.11</td>
<td>0.27</td>
</tr>
<tr>
<td>B</td>
<td>224</td>
<td>27</td>
<td>30</td>
<td>22</td>
<td>8</td>
<td>1.95</td>
<td>0.13</td>
</tr>
<tr>
<td>C</td>
<td>108</td>
<td>32</td>
<td>37</td>
<td>27</td>
<td>10</td>
<td>2.08</td>
<td>0.20</td>
</tr>
</tbody>
</table>
The modelled values for all regions, for both sampling dates, show a smaller range than was found by field measurement. This is due to the smoothing nature of the modelling algorithm where one or two measured values at the extremes of the range can be moderated by neighbouring values.

8.5 Tree density predictions across a wider area

All analyses to date have made use of tree density values based on the number of trees growing within a 5 m radius of each sampling peg. This number was converted to a density value (trees m\(^{-2}\)) as described in §7.1. It was not feasible to count each tree growing within the study area and so it was necessary to find a means of estimating the tree density across the site. Relatively recent aerial photographs of the site had been obtained and used to determine a 4 m grid of values indicating the percentage of tree cover falling within each grid cell. The procedure adopted is described in §6.2.3 with the generated grid shown as Figure 6.4.

In order to test the validity of this grid of tree coverage, the grid values for the twelve sample points were compared with the field data for those points. For consistency of comparison, a 5 m buffer was generated around each sample point using the GIS software, and the data from the grid squares falling within that buffer were averaged to give a value for percentage tree cover. Figure 8.5 shows the scatter graph of percentage tree cover obtained from the aerial photograph against the field measured tree density for all trees (larch, alder, oak and pine) within 5 m of the sampling peg. A logarithmic equation produced the best fit to the sample points with an \(R^2\) values of 0.88. The original planting scheme for the site (Table 5.3) indicated that larch, oak and alder would constitute 70% of the planting across the site, however findings in the field have shown larch and alder to comprise nearly 75% of the trees which have become established across the twelve sampling points (Table 6.6).
These two species occur at each of the twelve points, in contrast to the oak and pine trees which have failed in some areas. It was therefore decided to use the data relating to the larch and alder species as a basis for modelling tree density across the remainder of the field site. Figure 8.6 shows the equivalent scatter graph of percentage tree cover obtained from the aerial photograph against the measured tree density for larch and alder. Again, a logarithmic equation produced the best fit to the sample points with an $R^2$ values of 0.92. This equation was used to generate a grid of tree density within the limits of the study area as shown in Figure 8.7.

In order to validate the generated grid of tree density, a count was made of the number of trees falling within a 5 m radius of each of the twenty-five validation points. This count was used to determine a tree density value by dividing through by the area of the 5 m buffered zone (78.54 m$^2$). A scatter graph of the modelled tree density values for the validation points against the measured values for those points is shown in Figure 8.8. The trend line shows an $R^2$ of 0.72 and has a corresponding $p$-statistic of <0.0001.
Figure 8.6 Scatter graph of measured tree density (larch & alder) on % tree cover (from aerial photograph)

Clearly aerial photographs, provided that these are taken at an appropriate scale (in this case 1:8,300) and at a time of maximum foliage, can offer a very useful means of obtaining data to describe tree density across a restored site. However, it is recognised that the utility of this method will be limited by the age of the planted trees. As the canopy matures the likelihood of identifying individual trees will reduce. Moreover, further research would be needed to explore the possibilities of adapting the method to make use of aerial photographs taken during times of minimal foliage. The distribution, and success, of particular species across the site could be achieved through analysis of spectral response patterns obtained from remotely sensed data. Cost, data availability, and the time required for data processing impose limitations on this type of analysis and such modelling would seldom be appropriate for small-scale restoration schemes. This research has shown that the use of panchromatic aerial photography, in conjunction with a limited amount of field data for validation, can provide relatively cheap and accessible information regarding the levels of tree success across a study site.
Figure 8.7 Generated surface of tree density.
8.6 Bulk density predictions across a wider area

One hoped-for outcome of this research was the development of an algorithm whereby topsoil bulk density for restored soils could be predicted, with an acceptable level of confidence, from easily obtained field measurement of soil properties. This would provide useful additional information to the planning process, without the need for laborious and time-consuming determinations of the true bulk density.
Given that modelled grids were now available for a range of soil moisture, shear strength, and topographic variables and, bearing in mind the relationships (noted in earlier sections) between bulk density and a range of soil moisture characteristics, it was decided to attempt to model topsoil bulk density across regions A, B and C. The model used was that presented in Figure 7.4 where the main controlling factor was found to be the summer modal moisture value, supplemented by the winter range in moisture values, as described in §7.2.1.1. The model gave an $R^2$ value of 0.79 (adjusted $R^2$ of 0.74) with a $p$-statistic of 0.001. The regression equation took the form:

$$\text{predicted bulk density (Mg m}^{-3}\text{)} = 1.26 + 0.64 \text{ summer modal topsoil moisture (m}^3\text{ m}^{-3}\text{)} - 0.61 \text{ winter range in topsoil moisture (m}^3\text{ m}^{-3}\text{)}.$$

The generated grids of bulk density for the three regions are shown in Figure 8.9. Over the three regions the modelled values ranged from 1.19 to 1.37 Mg m$^{-3}$ with a mean value of 1.28 Mg m$^{-3}$. Data for bulk density was collected for twelve of the twenty-five validation points and used to explore to what extent this model of bulk density was effective. A scatter graph of the modelled bulk density values for the validation points against the measured values for those points is shown as Figure 8.10. The trend line shows an $R^2$ of 0.70 with a corresponding $p$-statistic of 0.0007 indicating that all of the variability in bulk density is not being accounted for by the two selected indicators of soil moisture. The intercept of the regression line fell at approximately 0.1 and it is interesting to note that the slope of the regression line is almost parallel with a 1:1 ratio line (shown in red on Figure 8.10). Moreover, all of the modelled values were between 0.03 and 0.11 Mg m$^{-3}$ lower than the measured values, being on average 0.08 Mg m$^{-3}$ lower. This would indicate that other parameters (possibly related to tree roots or pore size distribution) are systematically influencing topsoil bulk density and that the predictive strength of this equation could be strengthened by the inclusion of additional data in the modelling process.
Figure 8.9 Generated grid of topsoil bulk density.
This strong correlation between measured and modelled values indicates that the use of the soil moisture data can provide useful additional information on soil structure for inclusion in any planning processes.
8.7 Exploring the spatial pattern of vegetation success

Now that modelled grids for bulk density, topsoil thickness, winter shear strength and moisture range were available for the three test regions A, B and C; the next task was to study these grids in conjunction with the topographic data on slope, aspect and direction of drainage and explore their relationship to the level of tree success across the site. Two modelling techniques were investigated. The first technique to determine potential tree density is based on numerical modelling using a stepwise regression process. The second technique, to develop a 'tree potential' index, makes use of the techniques of multi-criteria analysis. Both methods generate grids of values which will be used in later investigations to identify areas for remedial action or additional planting.

8.7.1 Modelling tree density potential using regression analysis

Data values were extracted (from the modelled grids) for the twelve original sampling locations, and for the twenty five validation locations. These data were used to explore the relationships between both the topographic and soil factors and the tree density values for each of the thirty seven locations. An analysis of the data on tree density showed twelve of the points with values approaching zero. These points were excluded from the subsequent statistical analysis as the model was seeking to explain variation in tree density, and it was not possible to ascertain the limiting factor(s) leading to complete failure of tree establishment. A stepwise regression procedure was carried out using tree density as the dependent variable and the extracted values from the grids for bulk density, topsoil thickness, winter soil moisture range, summer modal soil moisture, winter shear strength, slope along drainage ridges, slope of land surface and the DIRDIFF variable (as discussed in §7.2.1.2 above) as the independent variables. From the original correlation matrix of tree density and these variables (Table 7.5) it was expected that bulk density, winter range in soil moisture, and winter shear strength would figure prominently in any model describing tree density.
predicted tree density (trees m\(^{-2}\)) = 0.337 + 0.012 \text{ slope (degrees)} + 0.001 \text{ topsoil thickness (mm)} - 3.143 \text{ winter range in soil moisture (m}^3\text{ m}^{-3}\)

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficient</th>
<th>SE</th>
<th>p</th>
<th>95% CI of Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.337</td>
<td>0.160</td>
<td>0.048</td>
<td>0.003 - 0.671</td>
</tr>
<tr>
<td>Slope</td>
<td>0.012</td>
<td>0.006</td>
<td>0.069</td>
<td>-0.001 - 0.025</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.001</td>
<td>0.000</td>
<td>0.100</td>
<td>0.000 - 0.002</td>
</tr>
<tr>
<td>Winter Range</td>
<td>-3.143</td>
<td>0.706</td>
<td>0.000</td>
<td>-4.615 - -1.671</td>
</tr>
<tr>
<td>Summer Mode</td>
<td>-0.504</td>
<td>0.213</td>
<td>0.028</td>
<td>-0.947 - -0.060</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>SSq</th>
<th>DF</th>
<th>MSq</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Due to regression</td>
<td>0.032</td>
<td>4</td>
<td>0.008</td>
<td>10.21</td>
<td>0.0001</td>
</tr>
<tr>
<td>About regression</td>
<td>0.015</td>
<td>20</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.047</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8.11 Regression model statistics for tree density based on data from modelled surfaces.
Strong cross correlation exists between these variables and it is statistically inappropriate to use all three variables in a regression model, given that each is seeking to explain the same portion of the variation in the tree density values. The stepwise procedure found that the best model for predicting tree density was based on four variables: soil thickness, slope of ground, winter moisture range, and summer modal moisture. The $R^2$ value returned was 0.67, adjusted to 0.61, and the regression statistics can be seen in Figure 8.11. Using this equation, the potential tree density across the site was calculated, based on the modelled soil conditions and their observed ability to support tree growth. The mean modelled value for region A was 0.08 trees m$^{-2}$ with a range of values from 0.03 to 0.12 trees m$^{-2}$. Within region B the mean modelled value was 0.12 trees m$^{-2}$ and a range of 0.02 to 0.25 trees m$^{-2}$. The model for region C gave a mean of 0.13 trees m$^{-2}$ with a range of values from 0.09 to 0.17 trees m$^{-2}$.

The restoration plan for the site specified a tree density in the order of 0.04 - 0.05 trees m$^{-2}$, allowing for a 20% failure in planting (§7.1), and in all cases the mean modelled value exceeds that specified density. The cell values from the modelled grid of potential tree density were categorised into bands of standard deviation about the mean. Figure 8.12 shows these bands, with the deepening shades of blue indicating areas of below average potential tree density, while an increasing intensity of red highlighting areas of above average potential. The dark blue areas are those which would be prime areas for the targeting of remedial activity. Within region A, 64 of the 133 grid cells (48.1%) fell below the mean value. Of these, 3 cells (2.3%) fell beyond two standard deviations, 25 cells (18.8%) fell between one and two standard deviations, and 36 cells (27.1%) fell within one standard deviation, of the mean. Within region B, 111 of the 224 grid cells (49.6%) fell below the mean value, with 41 cells (18.3%) between one and two standard deviations, and 70 cells (31.3%) within one standard deviation, of the mean. The modelled values for region C showed 49 of the 108 grid cells (45.4%) falling below the mean value of which 3 cells (2.7%) was beyond two standard deviations, 17 cells (15.7%) were between one and two standard deviations, and 29 cells (26.9%) were within one standard deviation of the mean.
Figure 8.12 Modelled tree potential based on topography and soil properties.
8.7.2 Modelling 'tree potential' using multi-criteria analysis

Multi-criteria analysis (MCA) is an appropriate modelling methodology when two, or more, criteria are instrumental in affecting the resulting value of a dependent variable (Malczewski, 1999). In this case, the analysis is based on four physical criteria of the topsoil for which model grids are available which show strong correlations with tree density and, for which, remedial action could be possible. These criteria are bulk density, topsoil thickness, winter shear strength and winter moisture range.

For each of these grids a linear equation was used to transform the values for each variable to a scale of 0.0 to 1.0, where 0.0 represents conditions that are inhospitable to tree growth and 1.0 indicates the best conditions for that variable, that were monitored on site.

To effect this transformation of scale, the equation:

\[ \text{scaled value} = \frac{\text{actual value} - \text{minimum value}}{\text{value range}} \]

was implemented for each of the criteria showing a positive relationship with tree density (topsoil thickness, winter shear strength and winter moisture range). The remaining criterion (bulk density) showed a negative relationship with tree density and so the above algorithm was modified to take the complement (to 1) of the scaled value, that is:

\[ \text{scaled value} = 1 - \frac{\text{actual value} - \text{minimum value}}{\text{value range}} \]

The scaled GIS layers for the four criteria can be seen in Figure 8.13. In all cases, the colours range from dark red for areas where conditions are inhospitable to trees, through to dark green where the best conditions across the three test regions can be found. These maps give an indication of topsoil conditions across the site, but must be interpreted with a few caveats in mind.
Figure 8.13a Grids for model parameters showing potential for tree growth

topsoil bulk density & topsoil thickness
Figure 8.13b Grids for model parameters showing potential for tree growth

- Topsoil shear strength
- Winter range in topsoil moisture

*Figure 8.13b Grids for model parameters showing potential for tree growth
topsoil shear strength & winter range in topsoil moisture*
For example, it may be possible to have areas where a low range in winter soil moisture values is indicated and where it could be assumed that trees have not established. However, this may not always be the case as a dense undergrowth layer can intercept heavy rainfall and delay the saturation of the surface soil. The presence of a substantial root network can also afford means by which water can be channelled deeper into the soil profile. This small range in winter soil moisture values might, therefore, be indicative not of waterlogged conditions, but rather of conditions where the soil remains drier than surrounding soils and never experiences anaerobic conditions. Under these circumstances, a low range in winter soil moisture values could be indicative of good conditions for supporting tree growth.

Similarly, the shear strength values may be affected, not just by soil structural conditions in terms of compaction or porosity, but also by the presence (or absence) of vegetation whose roots add strength to the soil matrix.

The next stage in the MCA is to determine a set of weightings for each of these criterion layers. This was achieved using a form of the Analytic Hierarchy Process (AHP) as discussed in §4.6.2. A series of pair-wise comparisons was carried out using the correlation with tree density (Table 7.5) as the input criteria in order to establish a priority ranking. So, for example, the correlation coefficient between tree density and topsoil thickness is 0.67, while that between tree density and winter soil moisture range is 0.87. In Table 8.9 the value in the 'topsoil thickness' column and the 'winter range' row will be $0.67 / 0.87 = 0.770$ while the inverse $0.87 / 0.67 = 1.299$ will appear in the 'winter range' column and the 'topsoil thickness' row. The fraction contributed by each column to the overall matrix total is calculated and used as the weighting factor in the MCA.
Table 8.9 Determining weights for the MCA criteria.

<table>
<thead>
<tr>
<th></th>
<th>Topsoil thickness</th>
<th>Winter shear</th>
<th>Winter moisture range</th>
<th>Bulk density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoil thickness</td>
<td>1.000</td>
<td>1.269</td>
<td>1.299</td>
<td>1.090</td>
</tr>
<tr>
<td>Winter shear</td>
<td>0.788</td>
<td>1.000</td>
<td>1.024</td>
<td>0.859</td>
</tr>
<tr>
<td>Winter moisture range</td>
<td>0.770</td>
<td>0.977</td>
<td>1.000</td>
<td>0.839</td>
</tr>
<tr>
<td>Bulk density</td>
<td>0.918</td>
<td>1.164</td>
<td>1.192</td>
<td>1.000</td>
</tr>
<tr>
<td>Total</td>
<td>3.476</td>
<td>4.410</td>
<td>4.515</td>
<td>3.788</td>
</tr>
<tr>
<td>Fraction of total (16.189)</td>
<td><strong>0.215</strong></td>
<td><strong>0.272</strong></td>
<td><strong>0.279</strong></td>
<td><strong>0.234</strong></td>
</tr>
</tbody>
</table>

The appropriate weightings were applied to the four scaled criterion layers, these weighted layers then being summed to produce a grid of values representing the physical soil conditions across the site. These soil potential values ranged from 0.0 (low potential, poor soil physical conditions for tree growth) to 1.0 (high potential, good soil physical conditions for tree growth). The resultant grid is shown in Figure 8.14.

8.8 Modelling tree growth potential

Now that grids of potential tree density and soil physical condition have been generated, it is possible to identify areas that might benefit from remedial action, and to determine which factors are restricting tree growth in those areas. Winter range in soil moisture showed the strongest correlation with tree density for the twelve sampling points, A1-C12 (Table 7.5) however, the regression model described above, based on 25 sets of data, shows topsoil thickness as contributing most strongly to the modelled values of potential tree density.
Figure 8.14 Index of 'tree potential' based on MCA methodology
Taken as a single, independent variable, variation in topsoil thickness can explain only 30% of the variation in tree density. It would seem likely therefore, that for certain areas, one or more variables may be imposing limitations on tree growth.

8.8.1 Determining areas for remediation

Four sets of analyses were carried out to determine the regions where tree growth may have failed to reach full potential, due to a combination of one, or more, of the factors. Each of these scenarios is identified in Table 8.10, and on the relevant diagrams by means of a code: Sc_1, Sc_2, Sc_3 or Sc_4. As low levels of vegetation success are evident in all parts of all three regions under investigation, and given the fact that, even in areas showing good establishment of trees, the planned stocking densities have not been uniformly achieved, it was decided to ascertain the 'worst case' value for each criterion in areas where the target density of 0.05 trees per m² has been achieved.

Table 8.10 Model scenarios of failure of tree planting.

<table>
<thead>
<tr>
<th>Scenario Code</th>
<th>Soil Conditions Restrictive?</th>
<th>Current Tree Density less than Potential Tree Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc_1</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sc_2</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Sc_3</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Sc_4</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

For bulk density, the appropriate scaled value was found to be 0.58; for topsoil thickness the value was 0.53; for winter shear strength, 0.47; and 0.44 for winter range in soil moisture. Using the weightings determined for the MCA modelling (Table 8.9), these values produce a physical soil potential of 0.51. Restrictive soil conditions are, therefore, deemed to exist in areas where the index of 'tree potential' (Figure 8.14) is 0.51 or below. The results for these scenarios are mapped in Figure 8.15 and summarised in Table 8.11.
Figure 8.15 Potential for remedial action across regions A, B and C.
(for code, see §8.8.1 and Table 8.10)
Table 8.11 Percentage of each region falling within each scenario.

<table>
<thead>
<tr>
<th>Region Reference</th>
<th>Scenario Sc_1</th>
<th>Scenario Sc_2</th>
<th>Scenario Sc_3</th>
<th>Scenario Sc_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>35</td>
<td>45</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>36</td>
<td>23</td>
<td>12</td>
<td>29</td>
</tr>
<tr>
<td>C</td>
<td>9</td>
<td>54</td>
<td>2</td>
<td>35</td>
</tr>
</tbody>
</table>

The areas categorised as Sc_1 (Figure 8.15) are those which should have the highest priority for remedial action. Not only are the physical conditions of the soil limiting tree growth, but even allowing for current soil conditions, the tree density currently falls below that which should be achievable.

Those areas categorised as scenario Sc_2 (Figure 8.15) warrant additional field investigation. The physical conditions of the soil under this scenario have been found, elsewhere within the study site, to be adequate to support the required density of trees. An Sc_2 categorisation indicates that the tree density currently falls below that which should be achievable. It may be that other factors (soil chemistry, vigorous competition with weeds for available moisture, the presence of a restrictive topsoil/subsoil interface) are acting locally to inhibit tree growth.

Similarly, category Sc_3 areas (Figure 8.15) warrant additional investigation in the field prior to remedial action being carried out. These areas have soil conditions which have been found to be limiting to tree growth and yet have achieved reasonable levels of tree success. Not areas of high priority, action taken at these locations to improve the physical condition of the soil could lead to more vigorous growth of the established tree stock.
Scenario Sc_4 areas (Figure 8.15) have soil conditions which are adequate to support successful establishment of trees. This is reflected in the acceptable tree densities achieved across these areas. No remedial action would be required on the soils at these locations, but thinning of the stock could lead to more vigorous annual growth of the established trees.

These scenarios have been built using a soil physical potential based on a weighted combination of values describing soil thickness, soil bulk density, shear strength and winter range in soil moisture. These parameters are inter-related, as shown by the cross-correlations evident in Table 7.5. By highlighting areas where remedial action is necessary, the implication is that, by bringing about an improvement in, for example, soil bulk density, a consequent improvement will be achieved in soil shear strength and soil moisture conditions. If it were necessary to look in more detail at the spatial patterns of the individual soil characteristics, the use of the grid manipulation routines within GIS makes this a very straightforward task. Rather than combining the physical soil factors into this grid of 'tree potential', the individual grids for soil thickness, bulk density, etc. could be interrogated and used to build scenarios for remediation.

8.8.2 Tree species variability

As well as identifying areas across the site where soil conditions could be improved, it was also decided to explore whether different species of tree favoured certain site conditions. Data had been collected at each of the twelve main sampling points for all of the oak, pine, larch and alder trees falling within a five metre radius of the marker peg (see §6.3.3). Girth measurements were taken in March and October. As trees had reached different levels of maturity at different parts of the site, and to allow for ease of comparison, the measured changes in girth were converted to a percentage increase. As only larch and alder were found at all sampling points, and as these two species were planned to account for 70% of the trees planted at restoration, further analysis concentrated on the data for these trees.
Figure 8.16 Change in tree diameter from spring to autumn for larch
Figure 8.17 Change in tree diameter from spring to autumn for alder
Figure 8.16 shows the measured diameters for the spring and autumn periods for larch while Figure 8.17 shows the equivalent for alders. On both graphs, a growth line has been marked to illustrate a 20% increase in diameter. The larch trees in region A, with the smallest dimensions, showed the greatest percentage increase in diameter with a mean increase of 18%, compared with 12% for region B, and 11% for region C. Alders in region B showed the greatest percentage increase of the three regions, clustering quite tightly around the 20% growth line with a mean increase in diameter of 16%. Alders in region A achieved comparable growth, with a mean of 14%, while in region C a mean growth rate of 9% was recorded.

Trees with the largest girth were found in region C, with more than one quarter of the alders measured returning diameters in excess of those measured at the other regions. Diameters of the larch trees in region C were of a similar order to those found in region B. The increase in growth for the two regions (B and C) was spread over a similar percentage range, with some trees showing between 6 and 7% increase and others showing a 23% increase over the sampling period.

It has been assumed that tree stock of similar age and health were planted at all locations across the site at the time of restoration, and it is known that no replacement of lost stock has been carried out in the intervening years. The age of the tree stock should, therefore, be comparable across the three regions. This implies that these differences in growth rates may be indicative of variation in the ability of the soil to support, and promote, healthy tree growth. The trees that have reached the greatest levels of maturity can be seen to be indicative of the best achievable growth across the study area. In an attempt to account for the possibility of differences in age and hardiness of tree stock (as percentage increases will be smaller in more mature trees of greater girth), it was decided to use total stem area as a means of comparing the relative health of the alder and larch trees between the twelve sampling points. As the diameter of each sampled tree had been recorded, and making the assumption that the stems were approximately circular, the area of each tree was determined using $\pi r^2$. 

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These calculated stem areas were totalled for each tree species, for each region. This means that the more successful points, with a higher density of trees, will have a higher value for total stem area. Similarly, if two points have the same number of trees, the point with the healthier trees will return a higher value for stem area. Computed values for total stem area ranged from 25 to 734 cm$^2$ for larch and from 46 to 918 cm$^2$ for alder. The data were transformed using a natural logarithm transformation in order to meet the linearity requirement for the subsequent regression analysis.

A stepwise regression analysis was carried out for each of the tree species to determine which of the topographic and soil physical variables could be used to explain the variation in stem area. For both the larch and alder data a very strong regression model could be developed to explain the pattern across the twelve points. Figure 8.18 shows the regression model and statistics for the larch species, while Figure 8.19 shows the equivalent for the alders. The larch model returned an $R^2$ of 0.90 (adjusted $R^2 = 0.86$) and a $p$-statistic of 0.0003 while the alder model was slightly weaker with an $R^2$ of 0.82 (adjusted $R^2 = 0.77$) and a $p$-statistic of 0.0011. Topsoil thickness came out as a significant factor for both species. Bulk density was a significant (negative) factor for the alders. A large amount of variability has been found in the patterns of rooting systems even within a single species (Lyford, 1975). In general, alders have been categorised as having a surface rooting system comprising large, horizontal main lateral roots extending just below the surface (Dobson and Moffat, 1993). The inclusion of bulk density in the model for alders is indicative of the need for less compact soils to facilitate the spread of this surface rooting system. It was interesting to note that none of the soil moisture variables were selected in the model for alders, reflecting the fact this species is tolerant of waterlogged conditions. The model for larch, in comparison, highlighted both the winter moisture range and the slope along the drainage ridges as being significant factors, indicating the need for well-drained and aerated soils.
Figure 8.18 Regression model to predict success of larch, based on soil and topographic parameters
Figure 8.19 Regression model to predict success of alder, based on soil and topographic parameters

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficient</th>
<th>SE</th>
<th>p</th>
<th>95% CI of Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>19.576</td>
<td>5.371</td>
<td>0.007</td>
<td>7.190 - 31.962</td>
</tr>
<tr>
<td>bulk density</td>
<td>-12.052</td>
<td>3.427</td>
<td>0.008</td>
<td>-19.955 - -4.149</td>
</tr>
<tr>
<td>topsoil thickness</td>
<td>0.013</td>
<td>0.007</td>
<td>0.102</td>
<td>-0.003 - 0.029</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>SSq</th>
<th>DF</th>
<th>MSq</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Due to regression</td>
<td>9.789</td>
<td>2</td>
<td>4.895</td>
<td>18.09</td>
<td>0.0011</td>
</tr>
<tr>
<td>About regression</td>
<td>2.164</td>
<td>8</td>
<td>0.271</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11.954</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The regression equations from these two models were implemented in the GIS and, using a similar procedure to that described in §8.7.2, scaled values for both larch and alder potential were determined for each of the three test regions based on the current site conditions. Figure 8.20 shows the potential for each of these tree species across the regions with tree potential values ranging 0.0 (low) to 1.0 (high). The shading on the maps ranges from dark red (low potential) to dark green (high potential).

The maps clearly show that there are some areas, particularly in regions A and B where current conditions indicate low potential for either larch or alder to survive. A large part of the unsuitable area for larch in region A (dark red), has a higher potential for supporting alder, indicating that, if this area were to be replanted without any action being taken to improve soil structural conditions, then alder would have a greater chance of successful establishment than would larch. Conversely, there are areas to the northwest of region B which are highlighted as having very low potential to support alder but have a higher potential for larch. Region C shows, overall, the highest potential for both species with only a small area to the east of the region showing potential values of 0.5 or below for either species. Over the entire extent of region C, alder would appear to be the better of the two species to plant, although the maps indicate that larch could be successfully interspersed in the most westerly limits of this region.

8.9 Summary

This chapter has provided insights into the fieldwork, the subsequent data analysis, and the model development phases of the research project. Data were collected for more than 30 topsoil variables, at twelve distinct sampling locations, covering three main regions within the study area. Some of these variables described the physical and structural characteristics of the soil, some gave an indication of soil chemical and nutrient status, and some indicated the nature of the soil moisture regime.
Figure 8.20 Growth potential for larch and alders
Supplementary data were collected, less frequently, at another twenty five points and used to validate the developed regression models. Analysis of the data from the twelve main sample points highlighted a number of interesting relationships. Strong correlations were found to exist between tree density (used as an indicator of the success of the initial tree planting regime) and topsoil moisture patterns throughout the year; between tree density and topsoil thickness; between tree density and soil bulk density; and between tree density and soil shear strength. The ability to predict soil bulk density from easily measured data describing soil moisture and soil shear strength was explored and tested against validation data. Investigation of a number of the modelled soil variables, in relation to patterns of tree density across the site, led to the development of a series of maps showing the potential for tree growth as constrained by soil thickness and soil structure. Four different 'improvement' scenarios were explored in order to identify which areas across the site could benefit from remedial action; while further investigation of the data collected for individual trees across the three regions allowed for the development of a growth potential index for alder and larch.

The collection and analysis of readily available field data seems to offer the potential to add significant value not just to the initial planning of planting schemes for restored sites, but also for remedial action should it prove necessary for parts of the site. In the next chapter, this potential for adding value will be discussed further in the light of the findings from this research.
Chapter 9. Discussion and directions for the future

"Tomorrow to fresh Woods, and Pastures new" John Milton (1608-1674)

9.1 Introduction

The impetus for this project stemmed from a visit to a research station based at the former British Coal 'Lounge' opencast mining site near the village of Coleorton in northwest Leicestershire. Being struck by the extent to which the restoration programme had failed to reach its potential in generating an economically and aesthetically productive site, questions were raised regarding the differential patterns of successful tree establishment across the area. These questions, in turn, highlighted the potential value (to the landowner, to wildlife, and to the local community) of developing a means whereby it would be possible to improve the levels of success across any given restoration project. Any such improvement would need to make sound practical and economic sense.

Cost is identified by Harrison (2000) as one of the three factors determining the treatment of 'problem' sites created by the mining industry (the others being scale and location). Planning guidance (MPG7, refer to Chapter 2) is designed to give priority to applications that will effect environmental improvement following mineral extraction. But there is an obvious need for such improvement to be monitored, and enforced if necessary. Harrison (2000) reports estimated costs for restoration of a 56.5 hectare site in Derbyshire to be in the order of £350,000 (at 1999 prices). This outlay of capital on restoration and tree planting becomes wasteful where restored sites are not effectively managed and maintained, and where, for example, the planned amenity woodland deteriorates into a wilderness of undergrowth and weeds.

There are a number of issues that can be addressed in order to reduce the potential for failure of tree planting in restoration schemes. Firstly, as discussed in Chapter 2, the initial reclamation process (including the stripping, storage, protection, replacement,
contouring and drainage of the soil) and the five year aftercare period are the responsibility of the mining company. Despite this obligation, the main business of the mining company is the extraction of minerals and it may have little interest in the longer-term (beyond the compulsory aftercare period) value or use of the restored ground. From the perspective of the mining company it makes most economic sense to reclaim the land as cheaply as possible and to use low-risk procedures that fulfil the legal requirements and ensure a timely conclusion to their aftercare obligations. It may be that five years is an insufficient aftercare period and that more restrictive regulations need to be put in place, however this would require funding for additional monitoring to ensure compliance. Alternatively, it may be possible to offer some economic incentive to the mining company (and the land owner) to ensure that the highest standards of restoration and aftercare are employed. This could take the form of a financial incentive based on the success of the restoration, and paid out, after a specified period of time.

Secondly, there may be a need to address some issues of standard forestry practice. The establishment of a vegetation sward can help to stabilise restored sites and reduce soil erosion (Wilson, 1986) but there is a risk that this vegetation will compete with the planted trees for supplies of water and nutrients (Bradshaw, 1980). Before the introduction of the Surface Mining Control and Reclamation Act (SMCRA) in the United States in 1977, herbaceous ground cover was rarely used on restored ground and tree seedlings often established easily and grew well (Jackson, 1991). Concern has been expressed among personnel involved in reclamation that the emphasis currently placed on the need for herbaceous ground cover can limit tree establishment and growth (Ashby et al., 1988; Davidson, 1989). Although sparse ground cover is not aesthetically pleasing it may be necessary to promote such an idea as being a necessary requirement for forest establishment. Mechanical or chemical removal of competing vegetation could then be employed in the early stages of reforestation. Torbert (1995) has shown that keeping ground cover to a minimum leads to increases in tree survival and growth without a significant increase in soil erosion. A reduction in both surface grading and ground cover has now been accepted as standard restoration practice.
within parts of the United States (Zipper et al., 2002), these conditions being seen as being consistent with best practice for forestry. Less grading leads to less soil compaction and therefore increased potential for tree survival and improved growth rates. There is an associated economic benefit as reported by Burger and Zipper (2002) who estimate that a reduction in grading and seeding can save $200 to $500 per acre.

Thirdly, there must be a recognition of the variation in soil conditions and the associated impact on tree establishment and growth. It is accepted that soil conditions will vary from one restoration site to another. The Forestry Commission is currently involved in a project, Roots, which aims to provide software to aid the preparation of specifications for establishing woodland on brown-field sites. Factors such as annual rainfall, altitude and coastal influence are considered in conjunction with soil properties when selecting species to be planted at specified sites (Robinson, 2002). Although useful for strategic planning, little account is taken of within-site variability which, as has been shown in this research, can impact on the success of woodland planting schemes. The rate at which trees grow is a function of site quality (Carmean, 1975; Avery and Burkhart, 1994). This site quality is a product of all of the factors influencing tree health: whether that be levels of competing ground cover and topsoil compaction affecting tree establishment; or the physical, chemical, and biological conditions of the soil affecting growth rates.

It is beyond the scope of this research to provide recommendations for legislative change to address the first two of the issues discussed above. Rather, this research has sought to provide a means by which site conditions can be measured and modelled, and planting schemes devised to ensure the best chance of success and an optimum return on investment. Two hypotheses were proposed to develop the research ideas. The development and testing of the first hypothesis provided a theoretical base for any recommendations for site improvements and offered a means of collating an empirical dataset for future modelling. This hypothesis stated that the variation in patterns of tree success across a restored site can be attributed to differences in soil properties. The
second hypothesis proceeded to test the manner in which current planning and planting strategies can be improved by means of detailed analysis and modelling of the field data. This hypothesis stated that the modelling of soil characteristics can provide additional value to the restoration planning process. Topsoil thickness has been found to be a significant factor affecting tree growth on restored sites (Perry, 1982; Scullion and Malinovszky, 1995). This research has focused on the extent to which the variability within a range of topsoil properties can be related to patterns of success when establishing new woodland. Further research would be required to determine the utility of such an approach as the trees mature and develop roots at greater depth. In order to test these hypotheses, data for more than 30 variables describing the topography, topsoil and vegetation across the study site have been collected and analysed. These data have formed the input to a range of statistical and spatial analyses which, in turn, have shown that an understanding of the large-scale variability in soil properties can offer useful information to support the design and development of planting regimes on restored opencast sites. This chapter discusses the extent to which the data, and the analyses, have informed the testing of the research hypotheses; gives some indication of the means by which site conditions can be improved; and proposes some areas for future investigation.

9.2 Testing the first hypothesis

"Differences in soil properties within the restored area are causing variation in the patterns of tree success." (§1.5)

9.2.1 Topography, soils and tree success

In natural forest stands, greater tree height growth is usually to be found on gentle slopes because steeper slopes tend to encourage greater runoff, shallower soils and increased soil erosion (Shoulders & Tiarks, 1980). In their research on restored sites, Andrews et al. (1998) found the opposite to be the case, with slope significantly
affecting tree growth, but with better growth being found to occur on steeper slopes. On reclaimed sites, slope steepness is often related to topsoil depth and levels of compaction (Andrews et al., 1998). It has been conjectured, in Chapter 3, that, on restored sites, areas of level ground may be subjected to increased vehicular traffic leading to greater compaction, poorer drainage and less well-aerated soils. The findings of this research substantiate this conjecture showing a negative correlation between slope (in degrees) and soil bulk density of $-0.28$ ($p<0.1$). A similar correlation coefficient (-0.29) was reported by Andrews et al. (1998) between slope and bulk density.

Slope plays an important role in establishing and maintaining conditions favourable to tree growth. The most direct function is that of controlling the removal of water from the land surface. Moffat and McNeill (1994) indicated slopes of between 5° and 6° as being necessary for efficient removal of excess water. In areas where slopes are less than 5° it could be expected that the annual soil moisture regime would prove inhospitable to tree growth.

A series of investigations were carried out focusing on the three sampling regions selected within the study area. Of the 465 grid cells comprising the three regions, 56% had slopes <5 degrees, the remainder having slopes of less than 10 degrees. The expectation, based on the correlation matrix derived from the field data collected for the twelve sampling points (A1 - C12), was that no significant correlation would be found between the slope of the ground and the patterns of tree density established across the site. Table 7.5 shows a Pearson correlation coefficient of 0.29 ($p<0.1$) between the measured slope and tree density values. Taking the data for all of regions A, B and C, the correlation between the slope (obtained by means of a detailed topographic survey) and the tree density (obtained by means of field survey and aerial photography) was a comparable 0.28. Figure 9.1 shows the scatter plot of tree density on slope for the three regions. The data have been subdivided into slopes of < 5 degrees, less than 7.5 degrees and < 10 degrees (which covers all of the slopes found
across the study area) and clearly shows that, even on the steepest slopes within the study area, there is no direct relationship between slope and tree density.

Figure 9.1 clearly shows that, at these low slope angles, there is no relationship between the tree density achieved and the degree of slope. Tree density values across region A are low, ranging from 0.0 to just 0.13 tree per m$^2$ nevertheless, the data show that higher tree density values have been achieved, on similar slopes, in other regions of the study site. This would imply that other processes must be affecting the level of tree success within region A. As discussed in Chapter 7, the gentle nature of the slopes across the study area, coupled with very slight changes in altitude, indicate that topographic factors, per se, are not the dominant factor controlling the success or failure of tree planting. Slope, in itself, does not directly impact upon the planted vegetation, and so it would seem that other soil physical factors are determining patterns of vegetation success.

![Figure 9.1 Modelled tree density on planar slope for regions A, B and C](image)
Figure 9.2a Patterns of topsoil moisture from March to October, 2001
Air photo showing areas of tree success

Photograph © Crown copyright. Ordnance Survey
Figure 9.2b Patterns of topsoil moisture from March to October, 2001
Volumetric soil moisture, 29 March 2001
Photograph © Crown copyright. Ordnance Survey
Figure 9.2c Patterns of topsoil moisture from March to October, 2001
Volumetric soil moisture, 26 April 2001
Photograph © Crown copyright. Ordnance Survey
Figure 9.2d Patterns of topsoil moisture from March to October, 2001
Volumetric soil moisture, 30 May 2001
Photograph © Crown copyright. Ordnance Survey
Figure 9.2e Patterns of topsoil moisture from March to October, 2001
Volumetric soil moisture, 26 September 2001
Photograph © Crown copyright. Ordnance Survey

Volumetric soil moisture (m$^3$m$^{-3}$)

- < 0.23
- 0.23 - 0.25
- 0.25 - 0.27
- 0.27 - 0.29
- 0.29 - 0.31
- 0.31 - 0.33
- 0.33 - 0.35
- 0.35 - 0.37
- 0.37 - 0.39
- 0.39 - 0.41
- 0.41 - 0.43
- 0.43 - 0.45
- 0.45 - 0.47
- > 0.47

0 50 metres
Figure 9.2f Patterns of topsoil moisture from March to October, 2001
Volumetric soil moisture, 31 October 2001

Volumetric soil moisture (m$^3$m$^{-3}$)

- <0.23
- 0.23 - 0.25
- 0.25 - 0.27
- 0.27 - 0.29
- 0.29 - 0.31
- 0.31 - 0.33
- 0.33 - 0.35
- 0.35 - 0.37
- 0.37 - 0.39
- 0.39 - 0.41
- 0.41 - 0.43
- 0.43 - 0.45
- 0.45 - 0.47
- >0.47

Photograph © Crown copyright. Ordnance Survey
9.2.2 Drainage, soils and tree success

Evidence gathered in the field indicated that certain areas across the restored site were prone to waterlogging during the winter months with this state continuing, in some areas, well into the spring. Figure 9.2 is a representation of the relationship between soil moisture conditions and the areas of successful tree establishment.

The first map (Figure 9.2a) highlights the areas of tree establishment displayed over an aerial photograph in order to facilitate locational referencing. Figure 9.2b to 9.2f show the patterns of topsoil moisture across the three sampling regions (A, B and C) for dates from March through to October of 2001. Looking at the areas where high levels of tree establishment have been achieved, in particular the area to the east of region B and that to the west of region C, it is clear from the maps in Figure 9.2 that the variation in topsoil moisture experienced in these areas is much greater than that in the areas of lower tree density. Referring back to Figure 7.1, the soil moisture data collected for the entire sampling period can be seen, and clearly illustrates this divergence in soil moisture between the points of lower tree density and those of higher tree density, in particular throughout the summer months. Spatial variation in the physical soil conditions offers some explanation of this divergence. It is likely that increased transpiration will be occurring at the more successful points where greater aerodynamic roughness promotes more vigorous uptake and use of soil water by the trees. The points of lower tree density (A1, A9, B5, B7 and C3) are consistently wetter than those points of higher tree density (in the order of 15% wetter during the winter months rising to 50% wetter during the summer). A more pronounced response of the topsoil to high intensity rainfall events can also be noted at the points of lower tree density (Figure 7.1) which would indicate a more efficient drainage of the topsoil at the points of higher tree density. These moisture patterns are indicative of the fact that the soils in the areas of successful tree establishment drain more freely; have a less compact structure; and contain a higher proportion of soil air: all of which conditions are beneficial to tree health and development which, in turn, leads to an increased uptake of soil water and the potential for continued improvement of the soil structure. Changes in the moisture pattern of the topsoil, in particular cycles of wetting and
drying during the summer months, can improve soil structure especially in the upper few centimetres of the profile (Blackwell et al., 1985; Bullock et al., 1985).

Given that surface drainage has been implemented across the study area by means of a ploughed system of ridges and furrows, the efficiency of these channels, in conjunction with slope characteristics, must also be taken into account. An investigation of the role of the imposed system of surface drainage was based around a comparison of the data collected from region B and that collected from region C. The imposed drainage in region B assists the movement of surface water into the drainage channels, while across region C the drainage runs parallel to the surface contour and promotes areas of standing water in the furrows. As the drainage furrows in region C have been ploughed in such a manner as to be ineffective in the removal of surface water, the expectation would be that, particularly in association with low slope, poorly drained areas would exist within this region with the topsoil being waterlogged for prolonged periods. If local topographical variation had been considered at the design stage such detrimental bearings for tractor and plough could have been identified and rectified prior to tree planting. By making use of data describing the local topography, it should be possible to fine-tune the restoration process to make the best use of site conditions. In dry lands, agricultural practitioners have long been aware of the benefits of contour ploughing both to decrease the potential for soil erosion and to promote infiltration of scarce water supplies to benefit plant growth. Conversely, in conditions such as are found on restored sites, where soils are compact and infiltration is slow, if the soil is sufficiently cohesive to withstand downslope movement, then ploughing along the slope can offer significant benefits for the removal of excess water. By taking into account the variation in the degree of slope, the concavity or convexity of the slope, and the physical soil properties, it should be possible to design a ploughing system to optimise the draining, or holding, of water across a restored site.

Figure 9.3 shows the range in volumetric soil moisture recorded over a twelve month period at the points with the highest tree density (B6 and C11) and the lowest tree
density (B5 and C3) within each region. Despite the differences in the ploughed system of ridges and furrows there is little difference in the range of soil moisture conditions experienced at both the 'best' and 'worst' points (where highest tree density equates to 'best' and lowest tree density to 'worst') of the two regions. The data show very clearly that the rate of the drying of the topsoil at point C3 is much more gradual than that experienced at points B5 and B7. These points within region B recorded their lowest topsoil moisture in July while point C3 returned its minimum value a full month later at the end of August (Table 7.3).

![Figure 9.3 Range in topsoil volumetric soil moisture.](image)

The rate of drying of the topsoil at the points within region C with intermediate tree density was comparable to that found at points of similar tree density within region B. These points have tree densities in excess of 0.1 trees per m² with this rapid fall in topsoil moisture being due, in part, to uptake by trees during a period of active growth. It is interesting to note that the modal moisture values for the (supposedly poorly drained) points within region C are lower than those recorded for the (more efficiently drained) region B. It must be remembered that the data for topsoil volumetric soil moisture were sampled from the ridge tops. Additional field testing on two occasions during the winter found the furrows to be wetter on average by $0.06 \text{ m}^3 \text{m}^{-3}$. On both occasions, the difference in soil moisture between the ridges and the furrows within region C was greater than was found in region B (Table 9.1).
Table 9.1. Difference in soil moisture between ridges and furrows.

<table>
<thead>
<tr>
<th>Sampling Date</th>
<th>average difference in soil moisture ($m^3/m^3$) between furrows and ridges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Region A</td>
</tr>
<tr>
<td>October '00</td>
<td>0.06</td>
</tr>
<tr>
<td>November '00</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The furrows within region C, running parallel to the contour, are obviously not moving surface water as efficiently into the river channel as those in region B. Nevertheless, they do seem to be effective in removing moisture from the ridges into the furrows, thereby allowing aeration of the topsoil on the ridges in the vicinity of the tree root systems. Given the high levels of tree success across most of region C it would seem that the imposed drainage system has not proved detrimental to the successful establishment of trees: indeed the additional storage of soil moisture within the ridges may be of benefit in times of low rainfall. Henning (1987) found a ridge and furrow system to create better conditions for tree growth than a level graded surface due to the retention of moisture in the furrows and the resistance to soil erosion by water.

It would be overly simplistic to attribute variation in the topsoil moisture regime solely to the ploughed system of drainage furrows. Strong relationships have been found between the soil structure, the soil moisture patterns and the levels of tree success achieved across the site. The empirical data collected within this project support the contention that the process of mineral extraction has damaging effects on topsoil. In common with other research, this study has found compaction, loss of structure, low porosity and restricted rooting depths to be prevalent on restored sites (Malik and Scullion, 1998; Armstrong and Bragg, 1984; Bussler et al., 1984).

Bulk density, and associated low macroporosity, often lead to slow percolation of water through the soil profile and to seasonal waterlogging (King, 1988). This tendency towards saturation under wet conditions can lead to the development of
anaerobic conditions with the associated difficulties of sustaining vegetation growth. Spatial variation in bulk density was observed across the study site and was found to correlate significantly with tree density \( (r = -0.73, p>0.01) \). A significant correlation was also found between bulk density and the winter range in topsoil moisture \( (r = -0.74, p>0.01) \) with those points having high topsoil bulk density, in particular points A9, B5 and C3 experiencing waterlogging of the topsoil during the winter months.

Research has shown topsoil thickness to correlate with better tree growth on restored sites (Perry, 1982; Scullion and Malinovszky, 1995). Andrews et al. (1998) found soil thickness to be the most significant variable affecting tree growth. In relation to explaining patterns of tree establishment, topsoil thickness was identified as being an important, although not the most important, factor. The correlation coefficient between tree density and topsoil thickness was \( 0.67 (p=0.02) \). Analysis of the data indicate a requirement for topsoil thickness in excess of 150-160 mm to achieve tree establishment at the required density.

9.2.3 Accepting the first hypothesis

The analyses support an acceptance of the first hypothesis. The variation in the patterns of tree success across the restored site did not occur by chance but rather can be directly attributed to variations in the soil properties and the associated effects on the environment in which the trees are struggling to survive.

A body of research has been established which shows that a deterioration of soil structure directly impacts on the potential for the successful establishment of trees on restored ground (Bending et al., 1991; Scullion & Malinovszky, 1995; Andrews et al., 1998). Scullion and Malinovszky (1995) indicate that there is a need for better use to be made of data describing basic soil properties in order to allow practical decisions to be taken regarding species suitability and ameliorative measures. Dobson and Moffat (1993) highlight the importance of evaluating the reasons for failure, prior to taking
remedial action, if tree losses are found to occur in large groups. A number of relationships have been identified between physical soil properties and patterns of tree success. The second hypothesis seeks to address the need for better use to be made of basic soil data by means of an exploration of the extent to which the modelling of spatial distributions of soil parameters can facilitate practical decision making and thereby add value to the restoration planning process.

9.3 Testing the second hypothesis

"The modelling of soil characteristics can provide additional value to the restoration planning process." (§1.5)

Dobson and Moffat (1993) state that the first rule of species selection for planting on restored ground is to choose what "will actually grow on a particular site" (p.52) with a failure to do so leading to heavy losses (requiring expensive replanting) or to retarded growth of the planted stock. This requires, in part, an understanding of the tolerance of particular species to a range of conditions, much research having been carried out in this area (Mason, 1999; Kennedy, 2002). Indeed research has been carried out to identify, or derive, clones of birch and willow which will survive best on restored soils (Good et al, 1985; Good, 1988).

Monitoring of soil conditions across restored sites is not a new phenomenon. Much research has been carried out regarding the effects of handling and storage on soil structure and chemistry (including Armstrong and Bragg, 1984; King, 1988; Harris et al., 1989) and within-site variation has been noted and discussed. Despite this broad base of research, little work has been carried out to explore the potential for exploiting site information at an appropriate scale in order to determine the suitability for locating particular species. GIS technology offers a means by which diverse sources of data can be stored, organised, manipulated and viewed within a common spatial framework;
variation in site conditions can be visualised and modelled; and patterns and relationships between factors can be identified and explored.

This research has illustrated the use of routines within GIS to manipulate field data in order to generate surfaces of topsoil thickness, volumetric soil moisture, topsoil shear strength and bulk density. The GIS provided a means by which aerial photography could be exploited to provide a comprehensive data set describing patterns of tree success across a wide area requiring a minimal amount of time consuming data collection for validation purposes. Using a GIS to provide a repository for all of the required data within a common spatial framework meant that visualisation and exploration of patterns and relationships became a (relatively) straightforward task.

9.3.1 Generating modelled surfaces

Geostatistical methods (kriging) were used to generate surfaces of topsoil thickness, soil moisture and topsoil shear strength in order to predict values at locations where sampling had not taken place. Strong correlations were found to exist between tree density and topsoil moisture patterns, thickness, bulk density and soil shear strength. With the exception of bulk density, these topsoil parameters are readily obtained by field measurement using portable and easily used hand-held tools.

The survey of topsoil thickness covered an area of 7700 m$^2$ and comprised 127 sample locations at each of which three cores were extracted using an open sided auger and the topsoil thickness measured and recorded. These (381) measurements were carried out over three site visits and required a total of approximately 25 hours of fieldwork. The use of the hand-held GPS proved invaluable for recording the positional information for each sample. Similarly, each of the detailed surveys of topsoil volumetric moisture and shear strength were completed within a single (8 hour) fieldwork day, as it was necessary that the data be collected under constant weather conditions and with as little
temporal variation as possible. Analysis, and subsequent validation, of the data allowed the development of a model for predicting topsoil bulk density based on the summer and winter topsoil moisture characteristics. The strong relationships between bulk density and the topsoil moisture regime offer a means of obtaining site-wide indicators of soil compaction and porosity without the need for time-consuming and expensive laboratory analysis. Research in the area of in situ measurement of bulk density (Tyler et al., 2001) may provide an efficient and cost-effective input to this modelling process.

The field sampling approach adopted in this research has provided an empirical dataset from which to explore and develop models of tree growth potential. The spatial variability of soil properties is central to such models. Time and cost constraints on field sampling may lead to insufficient data being collected to adequately describe spatial soil variability. Much research has been carried out into the use of remote sensing for the prediction of soil moisture (Engman, 1991; Shih and Jordan, 1992). Davidson and Watson (1995) reported the potential for using the thermal channel of an high resolution airborne imaging system as an indicator of gravimetric soil moisture. There is potential to develop this research by exploring the use of remote sensing and imagery to provide input data to the model.

Data on tree success formed a necessary input to this research. The answer to a question such as "How do we judge the success of tree planting?" will depend upon the person being questioned: be that the director of a mining company; a commercial forester; a wildlife expert; or a member of the local community. SMCRA uses the number of live trees per acre after specified periods of time to provide a (crude) indicator of tree planting success although some work is underway to include a measure of tree vigour (Ashby and Vogel, 1994). A similar approach was adopted in this research, where a tree density value was determined based on the number of live trees per square metre of land. In order to remove the requirement to count each tree within the study area, use was made of recent aerial photographs of the site to
determine the location and density of trees. The field validation of this technique afforded a high level of confidence in the method with $R^2$ values in the order of 0.9 between measured and modelled values. There is scope for more detailed research in this area. The use of aerial photography could afford a very cost effective means of monitoring site establishment over longer time periods. It may also be possible to use photographs from different seasons to assist in identifying patterns of success for particular species. It could also prove interesting to explore the potential use of airborne thermal and multi-spectral sensors to provide additional data on tree health and vigour.

9.3.2 Modelling growth potential

In their research on the restoration of native woodlands Lee et al. (2002) argue that the required increase in woodland could be achieved by random tree planting but that a spatially targeted restoration plan offers greater potential to maximise the ecological benefit. Similarly, in this research, the implementation of a series of spatial analyses afforded the opportunity to identify spatially targeted areas for remedial action. The GIS software made it possible to explore and manipulate the data describing soil and tree conditions across the three sample regions and to identify areas where various combinations of factors were assisting or proving detrimental to the establishment of particular tree species. With increased environmental awareness being reflected in the legislation (HMSO, 1999) and in public demands for a better quality of restoration (Burningham and O'Brien, 1994), any method that offers a maximised return is worthy of consideration.

The GIS-based method proposed in this research offers a number of benefits to restoration planning and planting:

- by tackling the restoration issue at a local scale, and taking into account within-site variability in soil parameters, the detail of that variability can be used to inform the decision making process;
• the methodology provides a means of accessing a diverse range of information for use by planners and decision-makers;

• the flexibility of the software allows the data to be analysed and manipulated in a variety of ways allowing multiple scenarios and potential solutions to be created and assessed;

• the data used can be readily obtained through field survey or derived from aerial photography;

• the systems requirements are a standard desktop PC running the inexpensive ArcView software;

• the flexibility of the approach affords the potential to add additional criteria into the decision making process should appropriate data be available.

It could be argued that the interactions between the various soil and topographic parameters are not modelled according to rigorous scientific principles. The development of a model affording that level of detail would offer little potential for practical use as cost constraints on data collection would prove prohibitive. Rather, this research proposes an heuristic approach and the use of an exploratory tool for the identification of target sites for remedial action.

9.3.3 Accepting the second hypothesis

The literature on environmental modelling highlights the need for more, and better, use to be made of empirical data; for more robust and practical models to be developed; and for such data and models to facilitate a more informed decision-making process. The potential benefits of the modelling approach adopted in this research, and discussed in the preceding sections, support acceptance of the second hypothesis. An understanding of soil characteristics and the development of models to assist in the targeting of restoration resources will add value to the restoration process.
9.4 A greener future for restoration

Opencast mining is a temporary land use that can provide unique opportunities for the improvement or development of land (Jackson, 1991). A combination of careful planning, design and implementation; coupled with a working partnership between the local community, the mining company and the legislative authorities; can bring about the valuable exploitation of coal reserves while minimising (or possibly, eradicating) associated environmental problems (Harrison, 2000). In becoming a signatory to the Biodiversity Convention at the Earth Summit in Rio, the UK agreed to Article 8(f) stating a commitment to 'rehabilitate and restore degraded ecosystems'. It follows that any methodology which can help to guide such rehabilitation must be worthy of consideration: be that the imposition of more restrictive aftercare conditions; the development of more vigorous tree species; or the use of tools to inform the planning process.

9.4.1 The need for aftercare

One of the best measures that can be implemented to ensure the success of any restoration programme is the enforcement of the aftercare conditions as laid down in the planning application. This aftercare period is designed to ensure that a suitable standard of restoration is achieved to facilitate the planned use of the site following restoration. Where the planned use includes the establishment of woodland such functions as cultivation, planting, weed control, protection from animals and fertilising would all form part of the aftercare programme (Dobson and Moffat, 1993). It has been recognised by government that restoration and aftercare were not always carried out to the required standards. In a ten-point plan for opencasting the Labour Party stated an intention to 'tighten the rules to secure prompt and full restoration of sites and ensure that funds to do this are available from the operators' (Dobson, 1996). Careful monitoring of the soils throughout the aftercare period is essential to ensure that appropriate works can be carried out to improve the soil structure if necessary.
(Harrison, 2000). The methodology proposed in this research readily lends itself to the monitoring and modelling of temporal changes in soil properties, providing a useful means of tracking any deterioration and highlighting potentially problematic areas at an early stage. Wilson (1986) identifies a number of ways in which failed restoration programmes can be treated and improved. In regions where tree establishment has failed completely, or if trees are still less than 1m in height and the site is sloping at more than 5°, there is the potential to carry out inter-row ripping. If this is not feasible (the trees are too tall, the site is too flat or too much damage would accrue) then the recommendation is for clear-felling, re-forming of the land, re-ripping of the topsoil and replanting. Similarly, if marshy conditions have been created in flat areas, the recommendation is to re-form the land in order to produce a freely-draining soil profile (Wilson, 1986). This research illustrates a means by which areas can easily be identified that meet the criteria for a range of treatments and improvements. Used prior to initial planting, within-site variation can be taken into account to maximise the likelihood of successful tree establishment. As a longer term approach for site monitoring and maintenance, problem areas can be identified and expensive remedial activity targeted accordingly.

9.4.2 Achieving optimal tree productivity

In the longer term, trees have an ability to improve soil conditions by decreasing bulk density. This may be due to increased organic matter and greater faunal activity within the soil, or by root channels penetrating the soil and being left by decayed roots (Moffat, 1991). While some research is underway regarding the development of faunal communities on restored ground (Armstrong and Bragg, 1984; Rushton, 1986; Scullion et al., 1988), future research could usefully be carried out to compare the rate at which restored sites achieve optimal biological productivity in support of tree establishment and growth rates. Research has been carried out to develop new planting techniques aimed at promoting more successful establishment of trees and shrubs in new areas (Hibberb, 1989; Williamson, 1992). Nevertheless, it has been demonstrated
that established woodlands, even those of considerable age, exhibit low species diversity (Peterken and Game, 1984) and there is a need for young plantations and new woodlands to be actively managed to ensure that they develop into the species rich habitats they were designed to be (Francis, 1995). The methodologies proposed in this research afford a means by which temporal patterns of tree health can be mapped in conjunction with changes in soil properties. Regular monitoring will allow areas of low, or declining, productivity to be identified at an early stage. The appropriate remedial action can then be taken in the most timely and cost-effective manner.

9.4.3 GIS as a tool for maximising environmental benefit

GIS has been used to great effect within this research project to explore and explain spatial patterns of soil variability. Although GIS have been available as a desktop tool for research for many years they have not yet been widely adopted with agricultural research. White et al. (2002) assessed the use of GIS within agronomic research and found that, of the 250 research papers under consideration, more than half gave no geographic context to their research; 60% based their research on the findings for a single location; and only 10% used more than four sample sites to account for spatial variation in the properties under investigation.

The ability of GIS to organise, model and present patterns of spatial variation in data offers scope to make use of such functionality in a range of applications. Increased awareness of spatial variability should lead to improved resource usage, regardless of whether those resources are environmental, ecological, financial or temporal. Cook and Norman (1996) identify spatial resource targeting as offering the best opportunity for maximising policy efficiency and enabling policy makers to set priorities and direct their limited resources accordingly. There are numerous examples of the use of spatial targeting for nature conservation within the UK (Wilson, 1997; Yeo et al., 1998; Woodhouse et al., 2000) and further afield (van Jaarsveld et al., 1998; Stoms, 2000). Lee et al. (2002) identify the potential of GIS as a tool for resource targeting in order
to adhere to the European Union's habitat and species directives, with particular focus on the establishment and restoration of native woodlands.

As shown within this research project, in the context of land restoration such resource targeting could ensure that the ploughing of drainage ridges takes into account the local topography; that tree seedlings are planted in areas offering the greatest likelihood of successful establishment; or that (potentially time consuming and costly) remedial activity to improve soil structure is carried out with an understanding of the within-site variation in conditions.

GIS offer the ability to store and manipulate large quantities of data, to integrate data from a variety of sources, and to manipulate those data at a variety of scales. This level of functionality affords considerable advantage over manual methods of analysis both in terms of speed and flexibility of approach. This research has highlighted the potential benefits to be gained from being able to explore spatial variability of soil properties and patterns of tree growth at a large scale. The ability to distinguish within-site variability offers the planner the scope to tailor tree planting schemes to reflect local conditions. This should result in a minimisation of the potential for failure with a consequent reduction in all of the associated costs.

9.4.4 Concluding remarks

This research has been the result of an interaction between a range of sub-disciplines: soil science, ecology, forestry, statistics and information technology. The unifying factor has been one of geographical space, and GIS has provided the tool for describing and modelling that space. The need for such an approach has been highlighted by Bouma (2001) who identifies a need to make such knowledge more accessible and more widely able to be used in decision making.
A means has been provided whereby problem areas can be identified within a restored site. Factors affecting the soil moisture regime have been shown to play a key role in determining the success or failure of planned schemes for establishing woodland on restored sites. An analysis of soil properties can assist in designing planting schemes that reflect the spatial variation within those soil properties and allow for targeted planting schemes reflecting the requirements of individual tree species.

There is scope for refinement of some of the ideas proposed, including:

- the inclusion of more detailed process-driven models;
- the incorporation of a greater range of model parameters;
- the utilisation of greater volumes of empirical data;
- an exploration of the potential for using remotely sensing and imagery data sources;
- the investigation of temporal change modelling.

The methodology developed will hopefully go some way towards ensuring that, wherever possible, the ideals of the planning process are achieved and our opencast sites are returned from desolate wasteland to productive woodland.
References


Appendix 1 Aerial photograph of the Lounge study site, flown in July 1999, showing location of ponds, drainage channels, access tracks, agricultural areas and points for soil bulk density measurement. Photograph © Crown copyright. Ordnance Survey.
A: Open Hole (Coal Pit)  B: Air Shaft  C: Old Coal Pit  D: Old Sand Pit
1: Spring Wood  2: Birch Coppice  3: Rough Park

Appendix 2.1 Extract from Ordnance Survey, 1:25,000 series (1948)
Appendix 2.2 Extract, reproduced from the 1994 Ordnance Survey 1:25,000 series with the permission of the Controller of Her Majesty's Stationery Office.
Appendix 2.3 Extract from aerial photograph, flown in June 1953
Appendix 2.4 Extract from aerial photograph, flown in July 1991

Photograph © Crown copyright. Ordnance Survey.

[Diagram showing two ponds labeled 'Lower pond' and 'Upper pond']
Appendix 4.1 Semi-variograms for interpolation of topsoil thickness.
Appendix 4.2 Semi-variograms for interpolation of topsoil moisture.
Appendix 4.3 Semi-variograms for interpolation of topsoil shear strength.
Appendix 5 Aerial photograph of the Lounge study site, flown in July 1999, showing location of sampling regions A, B and C. Photograph © Crown copyright. Ordnance Survey.