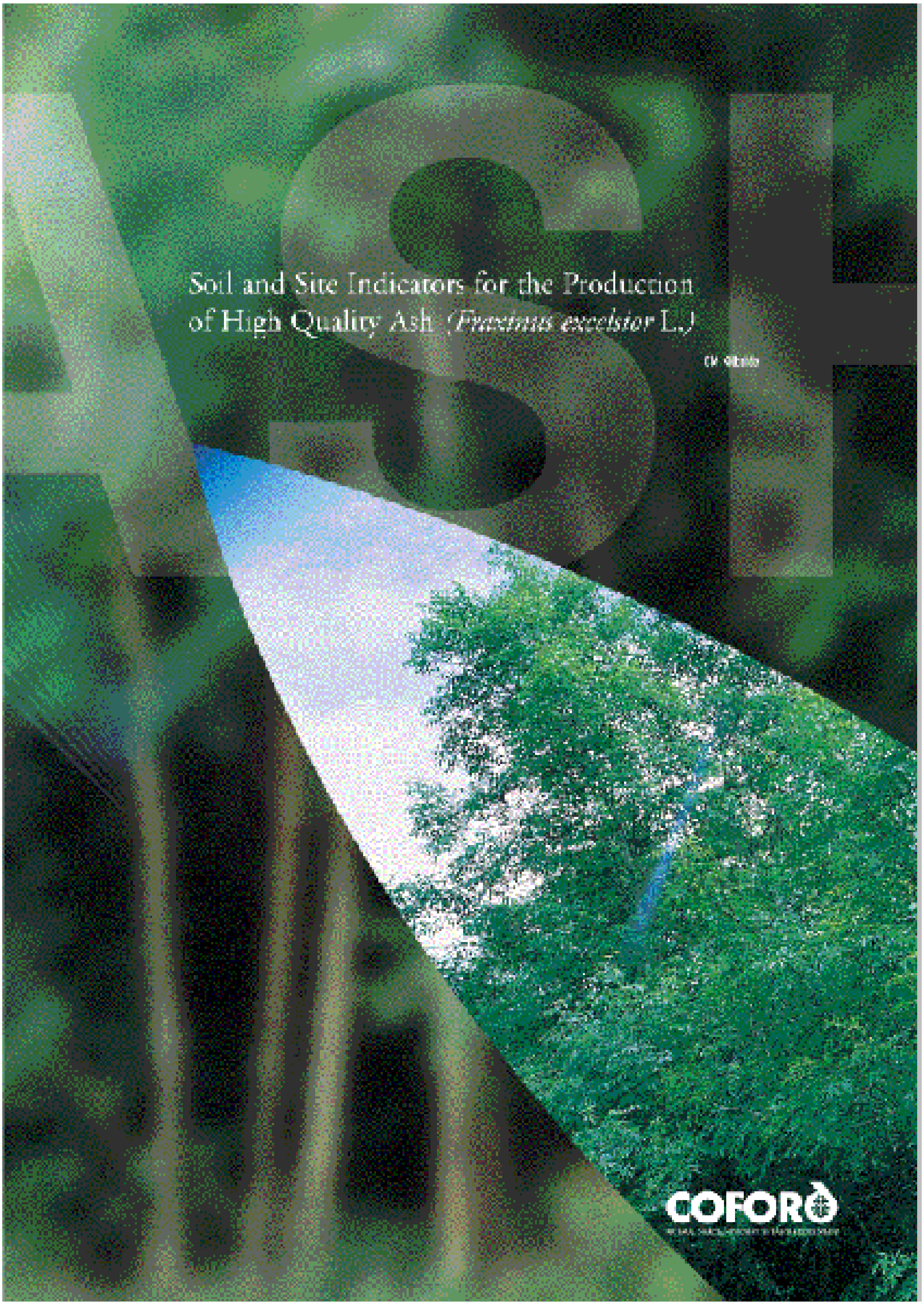

ASH
Soil and Site Indicators for the Production
of High Quality Ash (Fraxinus excelsior L.)
COFORD

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Foreword

There is an increasing emphasis on species diversification in Irish forests. This, along with the increasing availability of more fertile land for forestry and the higher grants and premia for broadleaves, means that there is a need for the same research into site suitability for broadleaves as was originally carried out for species such as Sitka spruce.

High quality ash is an ideal substitute for imported hardwood. However, it is a species which has not been studied in Ireland in any great detail. Ash is widely reported to be very exacting in its site type requirements. Therefore, for high quality crops, the ability to predict potential productivity on land available for planting is essential.

This COFORD report greatly increases the knowledge of the soil and site characteristics required to grow ash of the highest quality. This knowledge will be invaluable to the increasing number of forestry practioners and forest owners becoming involved in the thriving forest industry.

David Nevins
Chairman
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Executive Summary

Although it is widely recognised that ash (*Fraxinus excelsior* L.) is an exacting species with regard to its site requirements, little has been done in the past to assess site productivity.

In this study the productivity of a number of ash crops, between twenty and sixty years of age, was assessed. Soil and site variables were also measured at each site. The results are based on twelve sites. This is a relatively small number in studies of this kind and the results should be treated with caution.

Growth models for ash were derived by stepwise regression of the measured soil and site data on yield class (YC). The methodology employed is relatively simple and may be usefully replicated for similar studies on ash or other species. In the final model, Model 2, percentage sand was found to be the variable which explained 63.6% of the variation in ash growth on the YC4 and YC6 sites studied. This result indicates that the growth potential of ash may be closely correlated with the physical properties of the soil on which it is grown.

Considering the small number of sites in the study and the many limiting factors which were encountered, the final model explained a large proportion of variation in ash growth. It is recommended that the study should be expanded to validate the model and to include sites of higher productivity.

Section 1: Introduction

The opportunity to discover relationships between environmental factors and tree growth and hence the ability to evaluate variation in forest site productivity, has been an area of continuing interest in forest research for many years.

The term 'site' as applied to an area of forest land includes, but does not specify, the prevailing flux of environmental conditions. Observed tree growth is used as a measure of site productivity which reflects the response of the crop to these various environmental site factors. Each estimate of site productivity is a combined expression of all the environmental and biological variables which have influenced crop growth up to the time of measurement. Site evaluation studies, such as this one, attempt to isolate the numerous environmental factors which contribute to overall growth and determine what proportion of variation in growth each factor is accountable for.

To promote and foster a hardwood processing industry, diversification of species is meaningless if species are not matched to the site. The hardwood market requires high quality, knot-free material of adequate dimensions. Only species which are capable of reaching this high quality should be planted on any site.

Section 2: Literature Review

2.1 Natural Distribution of Ash

Ash is distributed in Europe from northern Spain to Norway and eastwards to central Russia. It ranges from northern Turkey to the Caucuses and may also be found in north Africa. It is widely distributed throughout Ireland and Britain (Nelson *et al.*, 1993 and Savill, 1991). McCracken (1971) reports that ash became established in Ireland after the major climatic fluctuations of the post-glacial age had given way to the type of climate which, with minor changes, has prevailed since about 500 BC.

2.2 Provenances

There is no knowledge of ash provenance variation in Ireland. Commercial planting stock is mainly derived from seed of unknown genetic worth. Negative selection of ash, due to the harvesting of trees of superior volume and form, results in phenotypically poorer trees providing seed for the next generation. Because very little information is available on variation within ash provenances, the current recommendation is to collect seed from straight, fast growing trees of good form. Ash currently grown in Ireland is primarily of Irish and English origin.

2.3 Site Type

Although some species thrive on a wide range of sites, others such as ash are very exacting (Savill *et al.*, 1986) and require high fertility, moisture, well oxygenated soil and little competition from weeds if they are to produce fast-growing crops. Joyce (1998) states that "compared to beech, sycamore and oak, ash has a high demand for nutrients, particularly nitrogen and phosphorus. To service this demand the soil has not only to be relatively high in nutrient levels, but also moist enough throughout the growing season to facilitate water mediated transport of nutrients to tree roots". As FitzSimons *et al.* (1986) state, the presence of prolific regeneration is not necessarily an indication of a suitable site as this regeneration may disappear after a couple of years.

Best growth is reported (Evans, 1984 and Savill, 1991) to be on deep, moist, freely draining, fertile soils of about neutral pH, but ash will grow on all soils above pH 5.5. However, according to Joyce (1998) the lower parts of the soil profile should approximate neutrality (pH 7.0). The high transpiration rate, and thus high water consumption, of ash (Jones, 1950) makes it prone to water stress which limits growth. Competition from weeds for both water and nutrients can be a problem especially in newly planted areas (Davies *et al.*, 1985). Joyce (1998) says that for Ireland, the ideal ash site is to be found primarily amongst the soils developed on limestone parent materials, namely brown earths and grey brown podzolics.

Ash is one of the most demanding species with one of the highest nutrient uptake requirements. This great demand for nutrients is possibly due to the fact that ash puts on all of its increment in a short period of time, from June to August. Wardle (1961) says that its preference for fertile soils is reflected in the high mineral ash content of the leaves and their rapid decay after leaf fall. It is reported (Anon., 1947) that a three year old ash transplant will extract from the soil four times the amount of potash, three times the amount of nitrogen and twice the amount of lime that is required by an oak seedling of the same age. As it is generally recognised that ash has extraordinarily high nitrogen requirements, nitrogen rich soils are particularly desirable. Poor growth on sites where it would be expected to do well is generally due to insufficient nitrogen supplies. The nitrogen requirement of ash is so high that on soils sufficiently high in nitrogen for other tree species and agricultural crops, ash is often hardly satisfied (Table 1).

Table 1: Yearly nutrient uptake for a range of species (Source: Savill et al., 1986)

Species & Location	Uptake kg/ha/yr		
	N	P	K
Douglas Fir *Second growth in USA*	39	7	29
Corsican Pine *Pole stage crop, Scotland*	22	6	28
Oak, hornbeam, beech *Belgium, 30 - 75 yrs. old*	91	6	52
Oak, **ash**, hazel *Belgium*	**123**	**9**	**99**
Birch *Fen in England*	56	4	28
Heather moorland	42	4	11
Unimproved grassland	44	4	25
Winter wheat	95	21	147
Barley	57	11	40
Potatoes (tubers only)	90	15	140

Although moist soil conditions are required for ash growth, prolonged flooding, water-logging or compacted soils will not be tolerated. Jones (1950) reports the sensitivity of ash to deficient aeration saying that as a result of this roots are markedly delayed in their growth and are often killed by a temporary rise in the water table.

Kassas (1950) agrees with Jones (1950) and reports on a study of ash on Chippenham Fen in Cambridgeshire. Analysis of growth rings revealed a strong relationship between high growth rates and periods of effective drain maintenance. He also reports that water-logging causes death of the submerged parts of the root system after a few days and that successful growth of ash will not take place on ground where the soil surface is less than 20 cm above the water table.

For successful growth of ash in Great Britain, favourable sites should be on a gentle slope at an altitude no greater than 230 m (Popert, 1950). Wardle (1961) states that a combination of exposure and unsuitable soil is probably responsible for determining the altitudinal limit of ash. He also says that northern limits may be set by intolerance of winter cold, and southern limits, at low altitudes, by hot summers.

2.4 Climatic Requirements

Evans (1984) states that the performance of ash in Britain is strongly site related. However the influence of climate on the growth of ash appears to be much less important than soil conditions. Ash is particularly susceptible to late spring frosts. Wardle (1961) reports that opening buds of seedlings will die after 17.5 hours exposure to a temperature of -3°C. Although most healthy plants will usually recover they will almost certainly be forked. Thus, planting in frost hollows should be avoided or else establishment should be carried out with the aid of nurses.

Shelter, both topographic and wood edge, against moisture stress appears to be essential for good growth. In general terms, exposed conditions lead to excessive transpiration and results in moisture stress. Weiser (1965), (*cited in* Roche, 1995) found that ash plants suffering from moisture stress produce more leaf hairs and smaller leaves in order to reduce the rate of evapotranspiration ultimately resulting in a reduced rate of growth.

The seedling stage is the only time that ash is shade tolerant. This initial shade tolerence means that ash is often classified as a pioneer species (Joyce, 1998). The ability of ash seedlings to withstand shading depends mainly on the amount of growth they can achieve before the expansion of the overhead canopy leaves cuts down the light to below the compensation point. The compensation point for net assimilation of ash seedlings was found to be at a daylight factor[1] of approximately 7% (Wardle, 1959). Wardle goes on to say that the rate of growth of a plant depends on the rate of assimilation per unit of leaf area, and on the total amount of leaf surface i.e. the Leaf Area Ratio[2]. When the overhead canopy is one of ash, the fact that the buds of the shaded seedlings open before those of the main canopy is of great benefit in relation to the amount of assimilation achieved. Most of the growth of seedlings is completed before the "dark phase" of full summer sets in (Wardle, 1961). Wardle (1959) reports a close relationship between height growth and overhead shade.

This is illustrated by measurements taken at Wyndcliff, Monmouthshire (Table 2). Plots were selected along a transect running from a clearing (upslope from the canopy edge) into the intact wood (downslope from the canopy edge).

Table 2: *Height growth of seedlings under varying degrees of overhead shade (Source: Wardle, 1959)*

Plot Position In Relation to Canopy Edge	Height (cm)	Growth 1954 - 1956 (cm)
13 yards upslope	473	57.0
3 yards upslope	251	34.0
2 yards downslope	204	23.0
8 yards downslope	71	9.5
14 yards downslope	16	1.4

From the results it can clearly be seen that open grown seedlings have the greatest height growth. When planting in mixtures it is important to remember that once ash is past the seedling stage the trees should always be kept open to full overhead light. This facilitates the development of a large crown which, in turn, facilitates rapid stem growth (Joyce, 1998).

Wardle (1961) reports that on the comparison of annual rings and monthly rainfall it was found that ash is especially sensitive to the amount of rainfall received in May and June, this dependence is apparent even on sites which are waterlogged during the winter months.

2.5 Vegetation Control and Establishment

At establishment stage ash does not compete well with grasses so previously unplanted sites will require a lot of vegetation control. The deleterious effect of grass is probably a matter of competition for nitrogen and water (Wood, 1950 and Wardle, 1961). However side shelter is still necessary to prevent stagnating growth due to exposure. This fact is highlighted in a study carried out on the effects of weed control on the establishment of ash (Culleton *et al*., 1995). Several treatments were applied including no weed control, 0.5 m strip[3] control, 1 m strip control and total weed control. The strip treatments were coupled with mown or unmown grass in between. The best result after three growing seasons was achieved by using a 1 m strip without mowing the untreated grass.

Culleton *et al.* (1995) suggest that the beneficial effect of leaving the unmown grass between the planted strips would appear to be as a result of the protection of the young plants from wind. Helliwell (1981) states that silvicultural treatment along with soil type and moisture availability could probably explain the differences in growth rates, form and quality of ash.

Culleton *et al.* (1992) agree with Davies *et al.* (1985) and state that the result of trials carried out at Johnstown Castle show that weed control is vital for the rapid establishment of ash. The area that was planted for this trial had previously been used for intensive beef production and up to 200 kg N/ha had been applied. The sward was burnt off completely with glyphosate

[1] Light received at a given locality, expressed as a percentage of full daylight, both quantities being measured under an overcast sky.

[2] Ratio of the leaf area to the total plant weight.

[3] A 'strip' in this context refers to a band of vegetation, along a row of planted trees, which is chemically controlled. The measurement given refers to the width of the strip e.g. 0.5m wide, 1 m wide.

three weeks prior to planting. After planting, complete weed control was practised in one area. In another area there was no weed control. In the area with no weed control grass growth severely restricted the growth of the ash and tree mortality, at 15%, was higher than in the weed control area where mortality was 4%. Tree height and diameter in the no weed control area were 34% and 37% respectively of that in the weed control area. There was a severe soil moisture deficit in the establishment year and also low rainfall in the following year. This suggests that lack of moisture may have been the main reason for the poor growth in the no weed control plots. Soil moisture deficit becomes greater under weeds than under bare ground.

It is recommended that an area of one square metre around the plant should be kept weed free for at least three years after establishment in order to maximise water and nutrient availability to the tree (Davies, 1987 *cited in* Kerr, 1995). Kerr goes on to say that an additional benefit of weed control is that the exposed soil is more efficient at absorbing heat than soil covered by vegetation. This warmth will improve plant root growth and overnight re-radiation may also reduce the risk of frost damage.

2.5.1 Stumping Back

If the initial form or growth of the ash is poor then stumping back should be considered (Kerr, 1995). This involves cutting back the stem to approximately 10 cm above ground level which stimulates resprouting, one of the new shoots can then be selected as a new straight stem. Madden (1945) reports on an area of ash planted in mixture with Norway spruce and an area of naturally regenerated ash, both growing on similar soil at Donadea Forest. In both areas the ash was crooked and deformed. Stumping back was carried out on both areas and one year later the naturally regenerated ash had sent out straight sturdy shoots with an average height of 86 cm. In contrast, the planted ash had sent up few shoots and those that had grown were crooked and diseased. Kerr (1995) also refers to a planted site in Herefordshire which had been stumped back. Ash had been planted in mixture with European larch but despite the protection provided by the larch the ash frequently suffered frost damage. After five years the ash was stumped back and subsequent thinning and pruning have produced an excellent stand.

2.5.2 Fertilizer Application

In a study carried out at Rockingham and Mortimer by Evans (1986) large increases in diameter increment of ash over three growing season following nitrogen fertilising were observed (Table 3). Two undergrowth treatments were combined with each fertilizer treatment:

Table 3: Diameter increment of ash between July '83 and October '85 (Source: Evans, 1986)

Treat-ment	Undergrowth left		Undergrowth cleared[4]	
	Rockingham (mm)	Mortimer (mm)	Rockingham (mm)	Mortimer (mm)
Control	5.51	3.80	6.26	3.81
K [5]	6.39	3.42	7.47	4.97
N [6]	6.82	5.35	7.39	4.69
N & K [7]	7.65	6.10	8.36	5.83

A fertilizer trial was carried out in Gorey Forest, Co. Wexford in 1978 on a 20 year old ash crop. The following treatments were used:

1. 1.5 tonnes of ground limestone/ha
2. 3.0 tonnes of ground limestone/ha
3. 3.0 tonnes of ground limestone + 800 kg 10:10:20 (NPK)/ha
4. 800 kg 10:10:20 (NPK)/ha
5. control

The results showed that from 1978 - 1980 there was a significant response in basal area increment to treatments 1, 2 and 3 with the NPK treatments both being better than the lime only. By 1983, the NPK treatments were still better but not significantly. This indicates that the response to these nutrients may only be short term and further applications may be necessary. The NPK only treatment was the best overall although the difference was not statistically significant. There was an increase in yield class from YC4 in 1978 to YC8 in 1983 in the plots which received 800 kg 10:10:20 (FitzSimons *et al.*, 1986). On the basis of these results FitzSimons *et al.* suggest that a positive response to applications of NPK can be expected in ash crops on mineral soils of less than YC10 which are neither waterlogged nor excessively dry.

In a study carried out by Gordon (1964) in the English Lake District height growth of ash was found to be closely related to foliar nitrogen concentrations. Almost 78% of the variation in height in the sampled plots was associated with N concentrations. The humus/nitrogen ratio in the soil was also found to be related to the foliar nitrogen concentrations. Sites with low humus to nitrogen ratios are likely to be sites with high nitrogen availability, resulting in higher foliar nitrogen concentrations in ash and consequently increased height growth.

2.6 Pure Crops

High quality ash results from fast growing crops. However, fully suitable sites are rare and small in area. Attempting to grow quality ash on sub optimal sites is not likely to be successful (Joyce, 1998). Large stands of pure ash tend to be prone to attack by ash bud moth and have leaders broken by wind (*ibid*). Heliwell (1981) says that on suitable sites a pure crop of ash will

[4] Chemical control to maintain clearing in subsequent years.
[5] Potassium 100 kg elemental K/ha applied as 200 kg/ha of muriate of potash.
[6] Nitrogen 150 kg elemental N/ha applied as 400 kg/ha of Nitram.
[7] Combined application of N and K as for individual treatments.

normally produce a greater annual increment of timber than oak, but less than beech. However he goes on to say that pure ash crops do not make full use of a site and the total volume production may be somewhat greater if the ash is planted in mixture as this allows for greater overall site utilization.

2.7 Mixtures

As ash is a frost tender species and is sensitive to exposure and moisture stress when young, it is often unsuitable for pure planting. As a light demanding species it has a crown of narrow leaves, usually allowing a relatively dense ground flora. Ash, being a shallow rooting species, has to compete with this ground flora for water and nutrients (Garfitt, 1989). Stevenson (1985) says that if ash is to be a final crop tree, best results are obtained by planting in mixture with another species.

Garfitt (1989) suggests that ash might be planted with beech or sycamore, both deep rooting species, in groups rather than intimate mixture. Kerr *et al.*, (1992) report on an experiment that was carried out in 1927 at Friston in south-east England. Ash was planted in several plots in mixture with a number of nurse species. At 30 years of age ash had made good growth in the plot with alder as the nurse, where the alder had spread by root suckering into the ash plots there was a marked improvement in ash growth also. Improved growth of ash in mixture with alder is probably due to the improved nitrogen supply. Kerr *et al.* (1993) suggest planting with Norway spruce or European larch in order to provide the necessary shelter. It often appears necessary however, to remove European larch early due to its rapid initial height growth. It is not uncommon for larch (YC12) to reach 8 m at 10 years of age compared with 3 - 4.5 m for other conifers (Kerr *et al.*, 1992). Helliwell (1981) agrees that ash and larch grow well in mixture and suggests removing the larch at about 30 - 40 years. Cotterell (1950) also suggests mixing with European larch, preferably with three to four lines of each species. Evans (1984) suggests mixtures with oak, beech or sycamore as well as European larch or Norway spruce. Helliwell (1981) reports on successful mixtures of ash and oak, the ash being removed at 60 - 80 years leaving the oak to grow on for another 40 years or so. Stevenson (1985) however, says that although ash and sycamore grow well together, if a final crop is envisaged it would have to be one of sycamore.

2.8 Management Practices

In order to achieve high quality crops of any species it is necessary to employ appropriate silvicultural practices. Management of a commercial crop is a continual process throughout its entire rotation.

2.8.1 Spacing

Spacing usually has a significant effect on height growth in broadleaved species - the wider the spacing the lower the height. This trend is evident in a trial carried out at Knocktopher, Co. Kilkenny (FitzSimons *et al.*, 1986). Initial spacing of ash varies depending on the end use of the crop. The Forestry Commission yield tables for 'commercial' ash are based on an initial spacing of 1.8m² (3,000 stems/ha). Current grant aided spacing of ash in Ireland is 2.0 x 1.5m (3,300 stems/ha).

2.8.2 Thinning

Ash thinnings (Evans, 1984 and Kerr *et al.*, 1993) should be heavy and frequent with the aim of keeping the crowns entirely free of competition. A live crown of one third of the height of the tree is recommended. If a tree is constrained and the crown becomes small, response to further thinning is poor. Once neglected, ash rarely recovers. One author recommends (Anon., 1955) that a moderately heavy first thinning should be carried out when a top height of 7.5 – 9 m is reached, paying particular attention to the removal of wolves and whips.

About three years later as many more of the misshapen dominants as can safely be spared should be removed. After another three years if the main crop has started to fill up the gaps a light thinning may be carried out. Subsequent thinnings may be intensified but it is essential to begin with light frequent ones.

Savill (1991) suggests that a crop should be at its final spacing by 30 - 35 years of age. Pruning may be necessary in order to prevent the development of large branches.

2.8.3 Rotation

Joyce (1998) specifies target diameters of 50 – 60 cm rather than a specific rotation length. However, he suggests that such diameters are achievable after a rotation of 60 - 80 years.

2.9 Pests

The ash bud moth *(Prays fraxinella)* is a major cause of forking in young ash plantations. Gent (1955) says that the ash bud moth selects the terminal bud because it is the largest and therefore provides the larvae with better protection during the winter and also the greatest and earliest supply of food.

Ash bud moth is widespread in Ireland. Quirke (1947) reported that it had been found attacking trees of all ages and that attacks were most severe on ash less than 20 years old. Gent (1955) showed how fast growing ash is less susceptible to attack. Gent also stated that seedlings under 2 feet tall appear to be more or less immune from damage, mainly because their buds are so small. The largest and fattest buds of the most healthy ash trees also appear to be somewhat immune, this is probably due to their rapid growth rates.

2.10 Wood Quality in Relation to Silviculture

To produce high quality timber (4-10 rings / 25mm) ash should be grown quickly. In ash (Anon., 1962) the pores of springwood (earlywood) are distinctly larger than those of summerwood (latewood). The summerwood consists mainly of thick walled fibres which give the wood its strength. The rate of growth, as shown by the width of the annual rings, and the proportion of summerwood are related to density and indirectly to strength. Slow grown ash is associated with low strength values because it contains a low proportion of summerwood (Anon., 1962). For practical purposes ash having less than 50% summerwood should not be accepted for constructional work unless density tests show it to be up to the required standard. The greater the proportion of latewood, the better its flexibility and bending ability. This renders it suitable for use as hurleys and tool handles where shock resistance and strength are essential.

Hurleys are manufactured from the butt log (bottom 1.5 m of the stem). It is therefore important that management of ash also result in a high grade timber (veneer or sawlog) in the rest of the stem. In a good stand, hurley ash will be harvested as thinnings with diameters in the range of 28–32 cm while the remaining crop should be grown on to a target diameter of 50 – 60 cm (Joyce, 1998).

Kerr (1995) recommends that ash should be felled in winter when the sap is down, otherwise the timber will split and crack due to rapid drying. At this time too the sapwood is less prone to damage by wood-boring insects (Savill, 1991).

2.11 Site Classification for Ash

Hägglund (1981) has suggested that the most widely used direct measures of site productivity are yield class[8] and site index[9]. However, a wide range of indirect measures, which rely upon the relationship between tree growth and site factors, have also been developed (Rennie, 1963). The most widely used site factors in this type of assessment are ground vegetation, soil and climate.

Although there is no direct relationship between tree growth and the composition of the ground vegetation, they are both to a large extent determined by the same site properties (Hägglund, 1981). Having said this, many sites are so extensively modified, both by cultivation techniques and also micro-climatically, that vegetation may be changed dramatically and so as a result be an unreliable indicator of site conditions.

Savill (1983) is of the opinion that soil is more relevant for classification purposes than vegetation, although this is mainly because vegetation is very complex and often difficult to sample objectively. Site classifications based on soil types can be extremely effective for making silvicultural decisions when establishing plantations (Toleman, 1979). However, it is generally recognised (Savill, 1983 and Pyatt, 1970) that, unless nutrient conditions are difficult, soil chemical properties are of less importance than physical properties for forestry classifications.

Climate can be one of the best indicators of forest productivity where the area under study is widespread or includes a wide range of elevations (O'Carroll, 1993 and Savill, 1983). Several studies have shown that climatic changes due to elevation are responsible for much of the variation in crop productivity (Worrell *et al.*, 1990; Toleman, 1979; Mayhead, 1973 and Fairbarin, 1968). Climate also influences many soil processes (Toleman, 1979). This may become apparent in winter when there is an excess of soil moisture in areas of high rainfall and soil leaching and water logging occur. In summer, areas of low rainfall suffer drought conditions and this along with high evaporation rates means the amount of effective rainfall can be low (Fairbairn, 1968).

It is clear that research into site classifications has long been a priority for scientists in many countries (Ralston, 1964 and Savill, 1983). The general approach has been to evaluate a range of site factors which are thought to influence the growth and productivity of the particular tree species under consideration. A multiple regression model relating productivity to site factors may be created using site factors as independent variables and productivity as the dependent variable. This model takes the form:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_nX_n$$

Where:
X_n = a site variable
a_n = the corresponding regression coefficient.

Since very little is known about site classification for ash, the same approach was adopted for this study. The objective of the study was to produce a mathematical model which can be used as an aid in identifying sites suitable for the optimal growth of ash.

[8] Yield class is a measure of the mean annual volume increment of a crop in cubic meters per hectare per annum.
[9] Site index is a measure of the height of a stand at a predetermined age.

Section 3: Materials and Methods

3.1 Study Area

Initially twenty-three ash stands, from various forests throughout the country, were selected from a database provided by Coillte. Of these original stands, twelve were eventually sampled following inspection. The location of these sites is shown in Appendix A. The other eleven sites were excluded from the study for a number of reasons. All stands selected from the database were between twenty and sixty years of age and any which were in mixture with another species contained at least 70% ash. Stands less than 0.5 ha in size were considered too small for inclusion in the study. Wherever possible fully stocked stands were sampled. However, a number of stands included in the study were poorly stocked. This occurred for various reasons including lack of management in some of the smaller stands and harvesting of hurley ash in a number of others. As there are no records of silvicultural or management practices for these crops, the effect of such treatments on crop quality could not be assessed. Therefore, the factors selected for measurement as estimates of crop quality (basal area, yield class and volume per hectare), are those influenced predominantly by site type. A summary of the information collected at each of the twelve sites is shown in Appendix B.

3.2 Field Methods

At each site a number of 0.01 hectare sample plots were set down. The number of sample plots, usually between six and eight, was dependant on stand area and uniformity. The 'top height tree'[10] in each of these sample plots was measured. Yield class of each crop was then determined using the Forestry Commission yield models for ash (Edwards & Christie (1981). Basal area was measured using a wedge prism relascope from a number of sampling points in each stand. The number of sampling points was dependent on stand area and uniformity but was usually between four and seven. Using the stand volume chart for ash the volume per hectare of each crop was determined. The procedures as laid down by Hamilton (1975) were followed.

Two 5 mm increment cores were taken from each top height tree using an increment borer. One of the cores was taken from the north facing side and one from the east facing side. Two cores were taken from each tree in order to encompass the variation in ring width that occurs around the circumference of any stem.

Two soil pits were excavated at each site in order to obtain soil samples. Their position was chosen randomly. Care was taken to avoid any areas that were uncharacteristic of the general site topography such as small hummocks or hollows. Two undisturbed soil samples, one at a depth of 5 - 10 cm and one at a depth of 20 - 30 cm, were taken for moisture availability determinations from each pit. This was done by inserting stainless steel cylinders (60 mm diameter x 40 mm deep) into the soil profile. These were removed and provided undisturbed soil samples. Loose soil samples for chemical and mechanical analysis were also taken from each pit, at the same depths as the undisturbed samples. These samples were oven dried at 30º C. They were then ground using a mortar and pestle and sieved through a 2 mm mesh.

The elevation for each site was taken from the ordnance survey map, aspect was assessed on the ground and exposure was assessed using the topex method, described by Wilson (1984).

3.3 Laboratory Methods

3.3.1 Annual Increment

Annual increment was measured on the increment cores using a digital callipers under a dissecting microscope at 6.5X magnification.

3.3.2 Available Moisture Content

Undisturbed soil samples were used in the determination of available moisture content. A linen gauze was placed on the bottom of the samples to ensure the soil remained undisturbed in the sample rings. The samples were then saturated from the bottom up by placing them in a water bath at ambient temperature. Once the samples were thoroughly saturated (a film of water could be seen sitting on the soil surface) they were removed from the water bath and weighed. They were then allowed to drain for 24 hours and were reweighed. This was equivalent to field capacity (FC) (Veichmeyer *et al.,* 1931). The samples were then placed in a high pressure ceramic plate extractor, as described by Klute (1986), and a pressure of 1,500 kPa was applied. Samples were retained at this pressure until their weight equilibrated. Equilibrium was deemed to have occurred when there was no change in weight after two or more consecutive weighings (a change in weight of less than 1 gram was accepted as equilibrium). This was equivalent to permanent wilting point (PWP). The samples were then oven dried at 105°C for 24 hours and reweighed. The Available Moisture Content (AMC) of the soil was calculated as:

AMC = (Vol. H_2O in soil at FC) – (Vol. H_2O in soil at PWP)

3.3.3 Soil Nutrients

Total nitrogen and extractable phosphorus, potassium, magnesium and calcium were measured using standard procedures described by Allen (1989).

3.3.4 pH

pH was determined using a 1:2 soil:water mixture.

3.3.5 Particle Size Analysis

Particle size analysis was carried out by sieving and pipette withdrawal as described by Gee *et al.* (1986).

[10] The tree of largest breast height diameter in a 0.01ha plot.

3.4 Statistical Methods

All data were analysed using the SAS statistical package (Statistical Analysis Systems Institute, 1995). A multiple regression model, to determine site productivity, was derived by stepwise regression of measured edaphic, climatic and topographic data on yield class. The stepwise method was chosen as it has been shown by O'Carroll (1993) to be appropriate to this type of study.

Section 4: Results

4.1 Site Characteristics

During the course of this study twelve sites carrying ash crops were examined. These sites ranged in size form 0.5 to 4.2 ha. Site characteristics such as elevation, aspect and exposure were evaluated. Site elevation varied from 8 to 122 meters. All sites were either moderately or very exposed, according to the topex classification described in Section 3.2, with the exception of the Templemore site, which was sheltered.

Table 4: Site variable estimates

Forest	Elevation (m)	Aspect	Exposure (Topex Score)
Allen	87	-	Very exposed (12.0)
Arigna	65	-	Very exposed (16.0)
Callan	122	-	Very exposed (18.0)
Callan3	92	-	Very exposed (18.0)
Castlepollard	122	S	Mod. exposed (40.0)
Comeragh	111	E	Very exposed (23.5)
Coolgreaney	55	S	Very exposed (12.0)
Ennis	32	-	Very exposed (15.5)
Lough Gill	8	-	Very exposed (16.0)
Monaghan	61	W	Mod. exposed (44.0)
Rathdangan	108	SW	Mod. exposed (39.0)
Templemore	92	W	Sheltered (64.0)

4.2 Crop Characteristics

The crops growing on the twelve sites were evaluated by measuring a range of parameters in randomly selected sample plots and sample points (Table 5). In this type of study it is desirable to have as wide a range of yield classes as is possible. Although the results shown in Table 5 indicate that only crops of YC2, YC4 and YC6 were measured, Yield Class was nevertheless chosen as the dependent variable to represent crop quality. Unlike mean basal area, volume per hectare and top height, yield class is largely uninfluenced by management practices. Since no management records were available for these sites, this was an important factor to be taken into consideration when choosing a measure of crop quality.

Table 5: Estimates of crop productivity

Forest	Planting Year	Yield Class	Mean Basal Area (m^2/ha)	Volume/ha (m^3/ha)	Mean Top Height (m)
Allen	1939	6	15.29	115	18.7
Arigna	1951	2	39.00	190	13.2
Callan	1952	6	33.50	230	17.3
Callan3	1965	4	17.80	80	12.6
Castlepollard	1936	4	24.00	186	16.0
Comeragh	1966	2	16.20	37	9.5
Coolgreaney	1958	2	22.80	92	11.8
Ennis	1951	2	25.70	82	10.6
Lough Gill	1940	6	18.50	140	18.5
Monaghan	1974	6	12.07	42	10.8
Rathdangan	1950	2	24.92	105	12.2
Templemore	1950	2	19.80	75	11.5

4.3 Climatic Characteristics

It was intended to compare rainfall with annual increment values. However, due to insufficient meteorological data for some sites this was not possible. Instead, an average May/June rainfall figure was calculated for each site from the limited data available (Table 6).

Table 6: Average May/June rainfall values

Forest	Rainfall (mm)
Allen	59.5
Arigna	70.1
Callan	67.8
Callan3	67.8
Castlepollard	69.1
Comeragh	54.0
Coolgreaney	56.6
Ennis	77.9
Lough Gill	54.4
Monaghan	66.6
Rathdangan	55.0
Templemore	59.5

Rainfall, as with all the other independent variables, was compared to yield class. The estimated average May/June rainfall data were quite uniform for all the sites. This may be due to the fact that records were incomplete.

4.4 Soil Characteristics

Soil samples were taken from each site for both mechanical and chemical analysis. Mechanical analysis (Table 7) showed some differences between sites in terms of particle size distribution. Available moisture content was also variable across the sites. Chemical analysis (Table 8) showed variation in terms of the levels of extractable P, K and Ca across the sites. However, total N and extractable Mg were more uniform. pH values ranged from approximately 4.50 to 7.50.

4.5 Data Analysis

A database was created containing all of the information that was collected at each of the study sites. Maximum, minimum and average values for this data are shown in Table 9. Using stepwise regression analysis, as described in Section 3.4, a model for the growth of ash was derived based on the information contained in this data base.

Table 7: Soil mechanical analysis

Forest	% Sand	% Silt	% Clay	% AMC Surface[11]	% AMC Sub Soil[12]
Allen	37.8	39.0	23.2	37.9	24.0
Arigna	44.6	25.3	30.1	54.6	53.7
Callan	43.3	23.4	33.3	38.8	37.4
Callan3	34.5	40.6	24.9	53.3	28.9
Castlepollard	17.7	40.9	41.4	31.7	44.7
Comeragh	33.3	44.5	22.2	72.1	67.2
Coolgreaney	40.5	28.3	31.2	35.2	18.1
Ennis	48.5	25.0	26.5	45.8	40.2
Lough Gill	54.3	31.7	14.0	74.6	50.0
Monaghan	54.6	18.3	27.1	36.4	26.6
Rathdangan	52.9	18.6	28.5	61.8	42.2
Templemore	49.6	33.4	17.0	45.4	35.4

Table 8: Soil chemical analysis

Forest	pH Surface	pH Sub Soil	Total N (%)	Extractable (µg/g)			
				P	K	Ca	Mg
Allen	5.99	6.03	0.45	25.50	61.25	3,536.25	250.50
Arigna	6.17	6.02	0.62	4.00	67.25	3,505.50	284.75
Callan	6.02	5.86	0.38	4.25	117.00	1,997.75	249.75
Callan3	5.87	5.76	0.53	3.50	109.50	2,417.50	230.50
Castlepollard	6.82	7.51	0.78	6.00	142.50	6,401.75	425.25
Comeragh	5.07	4.95	0.68	5.50	83.75	958.50	211.50
Coolgreaney	5.62	5.70	0.44	3.00	148.25	1,410.00	349.50
Ennis	5.67	5.57	0.52	5.00	63.25	2,214.25	232.75
Lough Gill	4.71	4.70	0.58	12.75	107.50	626.50	146.50
Monaghan	5.74	5.57	0.38	7.50	277.25	1,642.25	235.75
Rathdangan	5.68	5.32	0.68	4.50	266.75	3,293.50	389.75
Templemore	6.21	5.25	0.35	4.75	82.50	2,681.50	238.25

[11] Soil samples taken at a depth of 5 - 10 cm.
[12] Soil samples taken at a depth of 20 – 30 cm.

Table 9: Average and range of values for dependent and independent variables

Factor	Unit	Mean	Max.	Min.
Yield Class	m^3/ha/annum	3.67	6.00	2.00
Average May/June rainfall	mm	63.19	77.90	54.00
Sand	% by wt.	42.63	54.60	17.70
Silt	% by wt.	30.75	44.50	18.30
Clay	% by wt.	26.61	41.40	14.00
Surface available moisture content	% by wt.	48.97	74.60	31.70
Subsoil available moisture content	% by wt.	39.03	67.20	18.10
Total nitrogen	% d.m.	0.53	0.78	0.35
Extractable phosphorus	µg/g	7.19	25.50	3.00
Extractable potassium	µg/g	127.22	277.25	61.25
Extractable magnesium	µg/g	270.40	425.25	146.50
Elevation	feet	260.67	400.00	25.00
Surface pH (5 – 10 cm)	pH unit	5.5	4.7	6.8
Subsoil pH (20 – 30 cm)	pH unit	5.4	4.7	7.5
Age	years	42	59	21
Extractable calcium	µg/g	2,557	6,402	626

4.5.1 Model 1

Stepwise regression analysis of the complete database provided the following growth model:

Model 1
Yield Class (m^3/ha/annum) = 2.43 + 0.17 P (µg/g)

In this model extractable phosphorus accounted for 33.4% of the variation in ash growth on the sites examined. This result was significant at the 0.05 level. No other variable met the 0.05 significance level for entry into the model. The statistical output for Model 1 is presented in Tables 10 and 11. The derived regression line is shown in Figure 1.

Table 10: Model 1 analysis of variance output

Source	d.f.	Mean Square	F
P	1	12.9130	5.01 (p=0.0491)
Error	10	2.5754	
			r^2 = 0.334

Table 11: Model 1 parameter estimates and standard errors

Parameter	Estimate	S.E.
Intercept	2.4333	0.7197
P	0.1716	0.0766

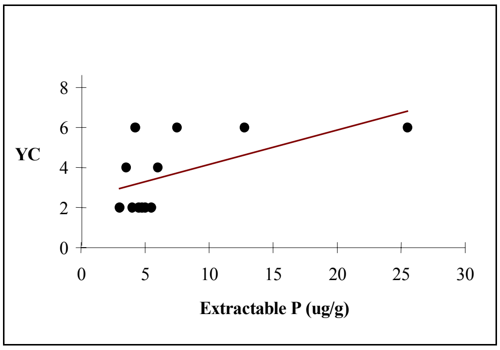

Figure 1: Regression line fitted to the measured yield classes for Model 1

4.5.2 Model 2

It was decided to remove the YC2 sites from the data base and run the stepwise regression procedure on the remaining YC4 and YC6 site data. The YC2 sites were omitted on the basis that sites achieving such low yield classes are probably unsuitable for the growth of ash and should possibly not have been planted with that species. Model 2 was derived by stepwise regression using the data from the YC4 and YC6 sites:

Model 2
Yield Class (m^3/ha/annum) = 2.93 + 0.06 Sand (%)

In this model percentage sand accounted for 63.6% of the variation in ash growth between the sites. This result was significant at the 0.1 level. No other variable met the 0.1 significance level for entry into the model. The statistical output for model 2 is presented in Table 12 and Table 13. The derived regression line is shown in Figure 2.

Table 12: Model 2 analysis of variance output

Source	d.f.	Mean Square	F
Sand	1	3.3919	6.99 (p=0.0574)
Error	4	0.4854	
			r^2 = 0.636

Table 13: Model 2 parameter estimates and standard errors

Parameter	Estimate	S.E.
Intercept	2.9340	0.9511
Sand	0.0594	0.0225

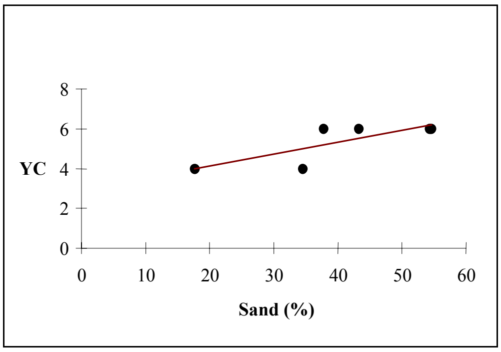

Figure 2: Regression line fitted to the measured yield classes for Model 2

4.6 Dependent and Independent Variable Correlations

Correlation matrices for Model 1 and Model 2 showed the relationship between the dependent variable, i.e. yield class, and each independent variable (Tables 14 and 15). In these correlation matrices the top row of figures, the correlation coefficient (r), indicates the type of relationship between the two variables in question. The value of r can be either positive or negative, ranging between -1 and +1. A value approaching -1 has a strong negative linear relationship, while a value approaching +1 has a strong positive linear relationship. A value of 0 may either indicate randomness or a more complicated type of relationship. The bottom row of figures in these matrices, the p-value, indicates the level of significance of the correlation between the two variables in question. The relationships observed in these correlation matrices (Tables 14 and 15) confirm the results obtained in the two models derived by stepwise regression.

In Model 1 extractable P was shown to have a positive influence on YC. Higher levels of extractable P resulted in higher yield classes.

In Model 2 percentage sand was shown to have a strong positive influence on YC. Higher levels of percentage sand resulted in higher yield classes.

4.7 Independent Variable Correlations

Tree growth is not a reflection of any single particular soil or site variable. It is the combined influence of many of these variables which actually affects growth. Therefore, some further analysis was carried out to examine the relationships between these independent variables. In order to see the relationships clearly, a correlation matrix was created for both the Model 1 data set and the Model 2 data set. The observed relationships are detailed in Tables 16 and 17. Some of the significant correlations highlighted in both the Model 1 and Model 2 correlation matrices were those which would be expected to occur. These include the highly significant correlations between surface pH and sub-soil pH and between elevation and aspect. Other correlations were not quite as obvious such as the significant relationship between aspect and extractable K. It is important, when calculating correlations between any pair of variables, not to assume that one causes variation in the other. It is possible that both may be affected by a third variable.

4.8 Main Findings

Although it would be of great benefit to produce a model with a small number of independent variables, which would accurately predict the potential yield of a site, this is not always as straightforward as it may seem. One of the difficulties in producing such a model is that interactions occur between the different independent variables. Very often it may be the combined effect of several variables which influences crop growth rather than any one particular variable on its own.

The correlation matrices produced for both Model 1 and Model 2 highlight the interactions which occurred between the variables which were examined in this study. Stepwise regression of the complete data set produced Model 1 which highlighted extractable phosphorus as the factor which accounted for the most variation in ash growth rates on the sites examined. Model 2 was produced from the YC4 and YC6 data. This model highlighted percentage sand as the factor which accounted for the most variation in ash growth.

Table 14: Model 1, Correlations between dependent and independent variables

	YC	Sand	Silt	Clay	MC surface	MC subsoil	pH surface	pH subsoil	N
YC	1.00 0.00	0.053 0.870	-0.013 0.968	-0.062 0.848	-0.196 0.541	-0.285 0.369	0.240 0.452	0.114 0.724	-0.301 0.342

	P	K	Ca	Mg	Elev.	Aspect	Exp.	Age	Rain
YC	0.578 0.049	0.140 0.665	-0.072 0.085	-0.345 0.272	-0.071 0.826	-0.270 0.395	-0.169 0.599	0.132 0.683	0.020 0.951

= Significant at the 0.05 level.

Table 15: Model 2, Correlations between dependent and independent variables

	YC	Sand	Silt	Clay	MC surface	MC subsoil	pH surface	pH subsoil	N
YC	1.00 0.00	0.797 0.057	-0.679 0.138	-0.485 0.330	0.143 0.788	-0.113 0.831	0.347 0.500	0.363 0.480	-0.699 0.122

	P	K	Ca	Mg	Elev.	Aspect	Exp.	Age	Rain
YC	0.482 0.334	0.103 0.846	-0.629 0.181	-0.606 0.202	-0.448 0.373	-0.122 0.817	-0.250 0.633	-0.025 0.963	-0.558 0.250

= Significant at the 0.1 level.

Table 16: Independent variable correlations for Model 1

	Sand	Silt	Clay	MC surface	MC subsoil	pH surface	pH subsoil	N	P	K	Ca	Mg	Elev.	Aspect	Exp.	Age	Rain
Sand	1.00 0.00																
Silt	-0.741 0.006	1.00 0.00															
Clay	-0.561 0.057	-0.140 0.665	1.00 0.00														
MC surface	0.294 0.354	0.144 0.656	-0.611 0.035	1.00 0.00													
MC subsoil	-0.112 0.729	0.230 0.473	-0.118 0.715	0.704 0.011	1.00 0.00												
pH surface	0.283 0.373	0.154 0.632	-0.608 0.036	0.736 0.006	0.439 0.153	1.00 0.00											
pH subsoil	0.361 0.250	0.150 0.642	-0.716 0.009	0.801 0.002	0.501 0.097	0.961 0.0001	1.00 0.00										
N	-0.488 0.108	0.321 0.310	0.324 0.304	0.405 0.192	0.654 0.021	0.203 0.528	0.160 0.620	1.00 0.00									
P	-0.002 0.996	0.270 0.396	-0.331 0.294	-0.048 0.883	-0.199 0.535	0.212 0.508	0.140 0.664	-0.117 0.718	1.00 0.00								
K	0.302 0.340	-0.570 0.053	0.257 0.421	-0.118 0.715	-0.252 0.429	-0.100 0.758	-0.076 0.814	0.022 0.945	-0.224 0.484	1.00 0.00							
Ca	-0.590 0.043	0.186 0.562	0.641 0.025	-0.473 0.120	-0.026 0.936	-0.572 0.052	-0.587 0.045	0.451 0.141	0.070 0.830	0.009 0.979	1.00 0.00						
Mg	-0.438 0.155	-0.117 0.717	0.790 0.002	-0.455 0.137	-0.162 0.614	-0.561 0.058	-0.574 0.051	0.430 0.163	-0.268 0.400	0.400 0.198	0.726 0.008	1.00 0.00					
Elev.	-0.561 0.058	0.277 0.383	0.486 0.109	-0.235 0.462	0.102 0.753	-0.547 0.066	-0.453 0.139	0.195 0.544	-0.159 0.623	0.123 0.702	0.497 0.100	0.489 0.106	1.00 0.00				
Aspect	0.085 0.792	-0.205 0.524	0.126 0.695	-0.251 0.432	-0.184 0.568	-0.245 0.442	-0.093 0.775	-0.061 0.851	-0.297 0.348	0.660 0.020	0.147 0.649	0.466 0.127	0.257 0.420	1.00 0.00			
Exp.	0.142 0.660	-0.138 0.668	-0.039 0.905	-0.227 0.478	-0.107 0.741	-0.294 0.354	-0.088 0.785	-0.130 0.686	-0.182 0.572	0.399 0.199	0.346 0.271	0.300 0.344	0.288 0.364	0.814 0.001	1.00 0.00		
Age	-0.215 0.502	0.192 0.550	0.081 0.803	-0.061 0.849	0.102 0.753	0.134 0.678	0.086 0.790	0.311 0.325	0.450 0.142	-0.362 0.247	0.536 0.072	0.250 0.434	-0.024 0.940	-0.254 0.426	0.039 0.903	1.00 0.00	
Rain	-0.149 0.644	-0.120 0.533	0.466 0.127	-0.471 0.122	-0.101 0.754	-0.504 0.095	-0.587 0.045	-0.054 0.868	-0.249 0.436	-0.190 0.554	0.360 0.250	0.057 0.859	-0.052 0.872	-0.318 0.314	-0.110 0.733	-0.028 0.930	1.00 0.00

: $0.5 \le p < 0.6$ = high correlation, $0.1 \le p < 0.5$ = significant, $0.01 \le p < 0.1$ = highly significant, $0.001 < p < 0.01$ = very highly significant.

Table 17: Independent variable correlations for Model 2

	Sand	Silt	Clay	MC surface	MC subsoil	pH surface	pH subsoil	N	P	K	Ca	Mg	Elev.	Aspect	Exp.	Age	Rain
Sand	1.00 0.00																
Silt	-0.742 0.092	1.00 0.00															
Clay	-0.721 0.106	0.070 0.896	1.00 0.00														
MC surface	0.489 0.325	0.084 0.874	-0.814 0.049	1.00 0.00													
MC subsoil	-0.081 0.878	0.091 0.863	0.027 0.960	0.474 0.343	1.00 0.00												
pH surface	0.547 0.261	-0.074 0.890	-0.738 0.094	0.904 0.014	0.642 0.169	1.00 0.00											
pH subsoil	0.580 0.227	-0.113 0.831	-0.746 0.089	0.905 0.013	0.628 0.182	0.999 0.0001	1.00 0.00										
N	-0.700 0.122	0.687 0.132	0.331 0.522	0.073 0.890	0.621 0.188	0.145 0.784	0.113 0.831	1.00 0.00									
P	0.130 0.806	0.250 0.633	-0.452 0.369	0.042 0.937	-0.277 0.595	0.166 0.753	0.143 0.786	-0.128 0.810	1.00 0.00								
K	0.342 0.507	-0.689 0.130	0.202 0.701	-0.289 0.579	-0.157 0.766	-0.152 0.774	-0.115 0.828	-0.218 0.678	-0.433 0.391	1.00 0.00							
Ca	-0.933 0.007	0.591 0.217	0.776 0.069	-0.653 0.159	0.042 0.938	-0.574 0.233	-0.605 0.203	0.675 0.142	0.012 0.982	-0.144 0.785	1.00 0.00						
Mg	-0.869 0.025	0.366 0.475	0.914 0.011	-0.745 0.089	0.077 0.885	-0.638 0.173	-0.659 0.155	0.600 0.208	-0.214 0.685	0.076 0.887	0.956 0.003	1.00 0.00					
Elev.	-0.734 0.097	0.211 0.688	0.874 0.023	-0.798 0.057	-0.250 0.633	-0.874 0.023	-0.886 0.019	0.095 0.858	-0.295 0.571	-0.123 0.816	0.685 0.133	0.753 0.084	1.00 0.00				
Aspect	-0.063 0.906	-0.363 0.480	0.468 0.350	-0.521 0.289	-0.081 0.879	-0.303 0.560	-0.285 0.584	0.152 0.773	-0.278 0.594	0.873 0.023	0.322 0.534	0.484 0.330	0.081 0.879	1.00 0.00			
Exp.	-0.236 0.653	-0.219 0.677	0.576 0.231	-0.551 0.257	0.028 0.958	-0.323 0.532	-0.313 0.545	0.326 0.528	-0.295 0.570	0.774 0.071	0.480 0.335	0.628 0.182	0.174 0.742	0.980 0.001	1.00 0.00		
Age	-0.431 0.394	0.556 0.252	0.066 0.901	0.103 0.846	0.554 0.254	0.285 0.585	0.241 0.645	0.594 0.214	0.479 0.336	-0.687 0.131	0.456 0.364	0.294 0.571	0.045 0.933	-0.349 0.498	-0.199 0.706	1.00 0.00	
Rain	-0.519 0.292	-0.068 0.899	0.841 0.036	-0.709 0.115	-0.262 0.616	-0.820 0.046	-0.808 0.052	0.044 0.935	-0.692 0.128	0.383 0.453	0.478 0.338	0.655 0.158	0.810 0.051	0.443 0.379	0.480 0.336	-0.435 0.389	1.00 0.00

(shaded) : $0.5 \le p < 0.6$ = high correlation, $0.1 \le p < 0.5$ = significant, $0.01 \le p < 0.1$ = highly significant, $0.001 < p < 0.01$ = very highly significant.

Section 5: Discussion

5.1 Objective

The purpose of this study was to determine relationships between soil and site factors and the growth of ash. It was hoped to identify one or two, easily measured, site characteristics which were closely correlated with the productivity of ash on a site. Specifically, it was hypothesised that the yield class of ash crops might be closely related to soil moisture availability during the months when the species is making most of its annual height growth. There are strong indications from the literature (Wardle, 1961) that a lack of available soil moisture may limit height growth during this period.

5.2 Crop Characteristics

A number of ash stands throughout the country were located and visited. Twelve of these crops were eventually used in the study. Some of the crops sampled in the study were understocked. This has a consequent effect on the validity of the results. In addition, many of the stands examined were quite limited in extent and it was clear that they had not been managed on a regular or systematic silvicultural basis. The reasons for such neglect may have ranged from economies of scale to harvesting of hurley butt material. This not only lowered the stocking levels of these stands but it also meant that trees of the best form were removed, leaving poorer quality trees to make up the final crop.

The quality of any crop can be greatly improved by applying appropriate silvicultural techniques, just as it can be reduced by neglect or poor silvicultural practices. No management records were available for the ash crops sampled. Therefore, it was not possible to assess the effect of silvicultural practices on crop quality. As a result, it was necessary to find an estimate of crop quality that was not influenced by management practices. At each site mean dbh, top height, YC, mean basal area and volume per hectare were measured. Of these, mean dbh, mean basal area and volume per hectare are influenced by stocking levels and hence management practices. Yield class, which is assessed using top height and age was chosen for use as the estimate of crop quality because "yield class is the maximum mean annual increment which a given crop can attain on a particular site, irrespective of treatment" (Edwards, 1981). Although Yield Class is considered independent of treatment, it would still have been useful to have had access to management records on initial stocking, use of nurse species and mixtures, tending operations, pruning and thinning. All of these treatments have a qualitative effect on the remaining crop.

Out of the twenty-three ash crops initially located for this study, only crops of YC2, YC4 and YC6 were found. Clearly a wider range of yield classes would be more appropriate for the purposes of this study. Sites attaining productivity outside of this range either could not be found or were unsuitable for inclusion. Evans (1984) reports that, on suitable sites, ash has the capacity for faster growth and higher productivity than either oak or beech, achieving YC10 or YC12. However, due to the widespread planting of ash on sub-optimal sites, the average growth rates are generally lower. Thus, it was not possible to find high quality crops of high productivity for inclusion in the study.

5.3 Site Characteristics

Generally the upper altitudinal limit for the growth of ash is probably set by a combination of exposure and unsuitable soil. All of the sites in this study were found at a range of elevations below the 230 m limit suggested for this species by Popert (1950).

Exposure was assessed by determining a topex score for each site. It is important to note that this assessment of exposure did not take into account elevation or aspect and their influence on the overall exposure of a site. Topex scores do, however, give a good estimate of the relative exposure of an area. They are probably most useful when used in conjunction with elevation and geographical location (Wilson, 1984). The majority of the sites in this study were rated as very exposed by the topex system. It is important to keep in mind that some of these ash stands may have been sheltered by adjacent tree crops either throughout their rotation or at some point during the rotation. Therefore, the exposure rating allocated by the topex system should only be used as a guideline when discussing the exposure of a site. It is rather extraordinary however, that of the twelve stands selected for examination in this study, eight occurred on sites which could be referred to as very exposed. Silviculturalists agree that ash grows best on sheltered sites. This probably accounts for the fact that the highest yield class encountered was YC6.

5.4 Soil Characteristics

The suitability of many of the sites sampled in this study for the growth of ash is questionable. In addition, many of the soils were very heavy. On all of the YC2 sites more than 50% of the particle size distribution consisted of silt and clay, with the exception of Rathdangan which was only slightly less at 47.1%. The Castlepollard site had by far the heaviest soil with 82.3% of the particle size distribution consisting of silt and clay.

One of the most easily measured and commonly tested soil factors, which is often used when deciding on species suitability for a site, is pH. It would be unusual to find ash crops planted on sites with unsuitable pH values. There was no great variation in pH values across the sites examined in this study. pH ranged from 4.7 to 7.5. Evans (1984) suggests that a pH value of 5.5 is relatively suitable for the growth of ash.

Ash has very high moisture requirements. Jones (1950), Wardle (1961) and Rushton *et al.* (1985) all report on the high water consumption of ash and consequently its sensitivity to moisture stress. Helliwell (1981) claims that moisture availability, along with site type, is responsible for explaining differences in ash growth rates. However, despite wide documentation of the importance of soil moisture in relation to ash growth, available moisture content in this study was not found to affect ash growth significantly. Available moisture levels ranged from 31.7% to 74.6% in the surface soil samples and from 18.1% to 67.2% in the sub-soil samples.

Ash is known to be a very demanding species with regard to its nutrient requirements. Even though it is recognised that ash requires higher levels of nutrients than many other tree species, the critical levels essential for the growth of ash have not been established. However, Wilde (1958) gives some guidelines concerning adequate soil nutrient levels for tree species in general. He puts these levels at 0.2% total nitrogen, 10 – 15 μg/g phosphorus, 150 μg/g potassium, 1000 μg/g calcium and magnesium should be one fifth to one third the level of calcium. The nitrogen and calcium levels of the sites in this study were well above these suggested levels. However, many of the sites had phosphorus, potassium and magnesium levels lower than the guidelines proposed by Wilde. Considering its exacting nature, sites with higher nutrient levels or alternatively, appropriate fertilizer applications, should be considered when growing high quality ash.

5.5 Climatic Characteristics

An average May/June rainfall figure was calculated for each site. There was no significant variation in rainfall levels between the sites with Comeragh having the lowest level at 54.0 mm and Ennis the highest at 77.9 mm. Rainfall, for this May/June period, was not found to have a significant effect on ash growth. However, the meteorological records were incomplete for many of the sites. Had a complete set of records been available, these results might well have been different considering the high moisture requirement of ash. Such records could usefully include average annual rainfall, average seasonal rainfall and average seasonal temperatures.

5.6 Data Analysis

All analysis was carried out using the SAS statistical package (Statistical Analysis Systems Institute, 1995). Stepwise regression analysis was the method used to derive the growth models as it has been used in similar site productivity studies carried out by Page (1976), MacMillan (1991) and O'Carroll (1993). The multiple regression models derived in this study were of the form:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_nX_n$$

Where:
X_n = a site variable
a_n = the corresponding regression coefficient.

This type of equation presumes that the relationship between site factors and productivity is a linear one. However relationships may for example be curvilinear. In such cases variables may be mathematically transformed in order to improve the model. As a result of this it has been argued that more complex models are necessary to describe these biological relationships accurately. Many of the independent variables which influence productivity are themselves correlated. Page (1976) attempted to minimise the effects of these inter-correlations by using principal components analysis on his data set in order to produce combinations of site factors which were themselves uncorrelated. Although this method was helpful in interpreting relationships in his data, he found that the results obtained were not superior to normal multiple regression for prediction purposes. It is on this basis that no transformations were applied to the data set used to create the models in this study.

5.6.1 Model 1

The stepwise regression analysis carried out on the complete data set produced Model 1. This model showed that extractable phosphorus was the independent variable which significantly affected ash growth, explaining 33.4% of the variation on the sites examined.

Phosphorus is mainly concentrated in seeds and the growing points of plants. It is an essential nutrient with regard to plant growth as it is involved in most metabolic reactions which occur within plants. The initial supply of phosphorus to the soil must come from the parent rock. Hence, in some habitats it can be a more critical nutrient than nitrogen, as atmospheric nitrogen can be made available by certain other plants and microbes. Another problem with the supply of phosphorus is that the low solubility of phosphates is a severe limitation on its availability to plants. The mean soil phosphorus level of the twelve sites examined was found to be *circa* 7μg/g, which is below the guideline set by Wilde (1958). Considering the importance of phosphorus in plant growth and the fact that it can be so unavailable in soils, it is reasonable to suggest that it may be limiting the productivity of ash on many of these sites. It is worth noting that phosphorus has generally been found to be the nutrient most frequently limiting the productivity of forest crops in Ireland (OCarroll, 1972). Thus, the relationship between soil phosphorus levels and productivity is understandable.

5.6.2 Model 2

Ireland has more favourable conditions for tree growth than many other countries. It was decided that sites achieving YC2 crops of ash should be removed from the data set on the basis that they should probably not have been planted with this species. Stepwise regression on the new data set containing the YC4 and YC6 sites produced Model 2. This model showed that percentage sand was the only independent variable which significantly affected ash growth, explaining 63.6% of the variation on these sites.

The main function of coarse soil material, i.e. sand and gravel, is largely confined to the physical support of plants. However, the proportion of sand in any soil determines the porosity of the soil which in turn influences its level of aeration and water holding capacity (Brady, 1990). The high water consumption levels of ash as well as its need for well oxygenated soils have been widely documented (Jones, 1950 and Savill *et al.*, 1986). Although ash requires very moist soil conditions, it is very intolerant of waterlogging. Soils dominated by sand generally possess good drainage and aeration properties, however this may cause problems in times of drought. At lower levels of sand there is a higher proportion of silt and clay in the soil. This fine soil material is responsible for determining the ability of a soil to retain moisture. The higher the levels of silt and clay the higher the soil moisture retention capacity. However this often means a reduced level of soil aeration. Model 2 shows that as the level of sand increases in a soil, so too does the yield class of ash achieved on the site. In this study the average sand content of the YC6 sites was 47.5% while on the YC2 and YC4 sites it was 37.4% and 26.1% respectively.

5.7 Independent Variable Correlations

In both Model 1 and Model 2 many correlations occurred between the independent variables. However a correlation between two variables is merely a relationship that occurs between them. It cannot necessarily be deduced that the variables influence each other in any way.

In Model 1 the concentration of extractable phosphorus was the independent variable which was found to have the greatest influence on YC. In the correlation matrix (Table 16) for this data set no other independent variable was found to be significantly correlated with extractable phosphorus.

In Model 2 percentage sand was the independent variable which was found to have the greatest influence on YC. In the correlation matrix (Table 17) for this data set a very highly significant negative correlation was found between percentage sand and the concentration of extractable calcium. A highly significant correlation was also found between percentage sand and the concentration of extractable magnesium. What these correlations mean is that, as the proportion of sand in the soil increases, the levels of extractable calcium and magnesium decrease significantly and *vice versa*. It is axiomatic that as the proportion of sand in the soil increases, the proportion of fine soil material, silt and clay, decreases. Clay particles have a large surface area and are electrically charged. This means they have the ability to hold nutrients in forms available to plants. Therefore, as the proportion of sand increases in a soil the proportions of clay and silt decrease and nutrients become less available to plants.

This correlation matrix also shows that there is a very highly significant positive correlation between extractable calcium and extractable magnesium. Therefore, in these soils wherever there is a high level of one of these nutrients there is a high level of the other nutrient. The reverse is also true.

5.8 Validation of the Growth Models

When validating any model which has been derived in this manner, it has been shown (Broadfoot, 1969 and McQuilkin, 1976) that the use of an independent data set is critical. However, due to a combination of constraints and the lack of suitable sites, this was not possible in this study. Since the models were derived from data collected from a total of twelve sites, it is clearly desirable to check their validity using data from additional suitable sites. Furthermore, the models presented should be tested over a range of yield classes.

5.9 Main Findings

A number of limitations were imposed on this study, including the small number of sites suitable for sampling, the small range in yield classes and the quality of some of the ash crops. However, the final model (Model 2) suggests that 63.6% of the variation in productivity in ash crops between YC4 and YC6 can be accounted for by the percentage sand content of the soil.

In general terms this model indicates that on sites with soils containing higher levels of sand, ash crops will achieve higher rates of productivity. Obviously there will be a cut off point where the proportion of sand to silt and clay in a soil is so high that it produces an adverse affect on the growth of ash through its impact upon for example, soil moisture retention. Since this model was derived using data from only YC4 and YC6 sites this situation was not encountered and therefore was not taken into consideration in the construction of the model. It is not wise to extrapolate from this range in yield classes and presume that the model can be applied when predicting higher yield classes of ash growth. In order to do this, higher YC ash crops should be included in the original data set used to derive the model.

The inclusion of some other independent variables such as management interventions and detailed meteorological data would also create a more holistic model.

Section 6: Conclusion and Recommendations

The difficulty in locating large enough and fully stocked sites limited the number of sites which could be sampled and included in this study. Despite this, a model was derived which identified one soil variable, percentage sand, as being the factor which was responsible for explaining 63.6% of the variation in ash growth on the sites examined. If this type of result can be achieved from data gathered from such a small number of sites with such a narrow range of yield classes, the percentage variation explained might be greatly increased by enlarging the study area.

Several aspects of this study could be improved upon in order to obtain a result which explains an even greater proportion of the variation in ash productivity. Ideally, only fully stocked stands which have received good or standard management should be included in the study. Management records should be available in order to assess the impact of silvicultural practices on crop productivity. Irrespective of the suitability of a site for the growth of ash, high quality crops will only be produced if the appropriate silvicultural treatments are applied throughout the rotation. The type of information which would be of benefit includes time and rates of fertilizer applications and weed control treatments as well as the volume of timber removed and the age of the crop at the time of thinning.

When creating a growth model such as this, endless variables can be measured and their influence on crop productivity estimated. As Ralston (1964) points out, the analysis of environmental factors related to site quality need not be all-inclusive but merely sufficiently detailed to include all the important variables and sufficiently astute not to overlook any of them. Therefore, it is important to focus attention on the elements of the total environment which appear to be relevant to the purposes of the study being undertaken. It is important not to lose sight of what this type of model will ultimately be used for. Models such as those produced in this study will primarily be used as tools which can be used to assist species selection decisions. In order for these models to be put into practical everyday use, they should ideally account for two or three site variables which explain a large proportion of the variation in crop productivity and which can be easily and inexpensively measured.

Despite the difficulties encountered in this study, there are clear indications that soil analysis, particularly in relation to percentage sand and the concentration of extractable phosphorus, may yield valuable information in the identification of high quality ash sites. This study should therefore be used as a starting block for a much more detailed investigation into site suitability for ash. By identifying a larger range of suitable ash crops and in particular ones of higher yield classes, further soil analysis can be carried out to validate the two models presented. Particular attention should be paid to the soil variables which were shown to influence the productivity of ash in this study. With data collected from a greater range of sites the results obtained in this study can be verified and perhaps improved upon.

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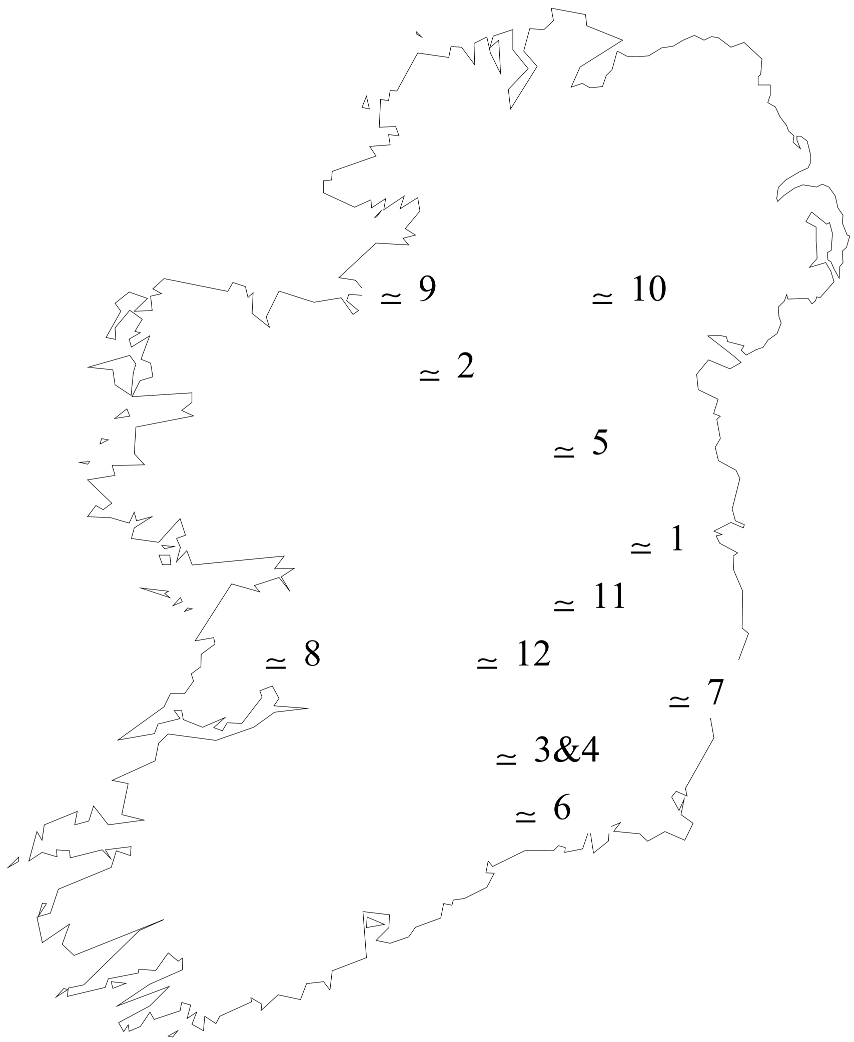
Appendix A: Site Locations

Number on Map	Forest
1	Allen
2	Arigna
3&4	Callan
5	Castlepollard
6	Comeragh
7	Coolgreaney
8	Ennis
9	Lough Gill
10	Monaghan
11	Rathdangan
12	Templemore



Appendix B: Summary of the Information Collected at Each Site

Forest	Property	Compt.	Area (Ha)	Elevation (m)	Aspect	Topex	Planting Year	Crop (% Ash)	Yield Class	Vol / Ha (m^3 / ha)	Mean Basal Area / Ha (m^2 / ha)	Top Height (m)	Predominant Vegetation	Other Comments
Allen	Donadea	263J (8)	3.0	87	-	12	1939	100	6	115	15.3	18.7	Ivy, some Bramble	Beech understorey
Arigna	Knockcranny	164K (2)	3.2	65	-	16	1951	100	2	190	39	13.2	Moss	Hurley Crop Removed
Callan	Castlemorres	357C (13)	1.1	122	-	18	1952	100	6	230	33.5	17.3	Ferns, Bramble, Bluebells	
Callan	Castlemorres	359P (3)	0.8	92	-	18	1965	100	4	80	17.8	12.6	Bramble, Ferns, Grasses	Hurley Crop Removed. Much Forking in Remaining Stems
Castlepollard	Mullaghmeen	314T (5)	2.1	122	S / SE	40	1936	100	4	186	24	16	Ash & Beech Litter Covered the Ground	Quite a Sheltered Site, in a Hollow. Many Crooked Stems
Comeragh	Kill Road	635B (3)	1.5	111	E	23.5	1966	100	2	37	16.2	9.5	Grasses, Bramble	Single Mould-Board Ploughed
Coolgreaney	Keers	740W (4)	0.7	55	S	12	1958	100	2	92	22.8	11.8	Bracken, Bramble, Grasses	Single Mould-Board Ploughed in N-S Direction. Orange mottling in soil.
Ennis	Dangan	453M (1)	1.3	32	-	15.5	1951	100	2	82	25.7	10.6	Grasses, Moss, Ivy, Bluebells	Very Rocky Site
Lough Gill	Hazelwood	805R (6)	0.8	8	-	16	1940	100	6	140	18.5	18.5	Bramble	
Monaghan	Castleshane	122G (8)	1.0	61	W	44	1974	70	6	42	12.1	10.8	Ivy, Bramble	Much Sprouting from Thinnings / Stumping Back
Rathdangan	Mullaghreelan	041N (5)	0.5	108	SW	39	1950	100	2	105	12.9	12.2	Bramble, Ivy	
Templemore	Goldengrove	903W (6)	4.2	92	W	64	1950	100	2	75	19.8	11.5	Bluebells, Bramble, Ivy	Beech Understorey. Ash Stems Quite Straight in General