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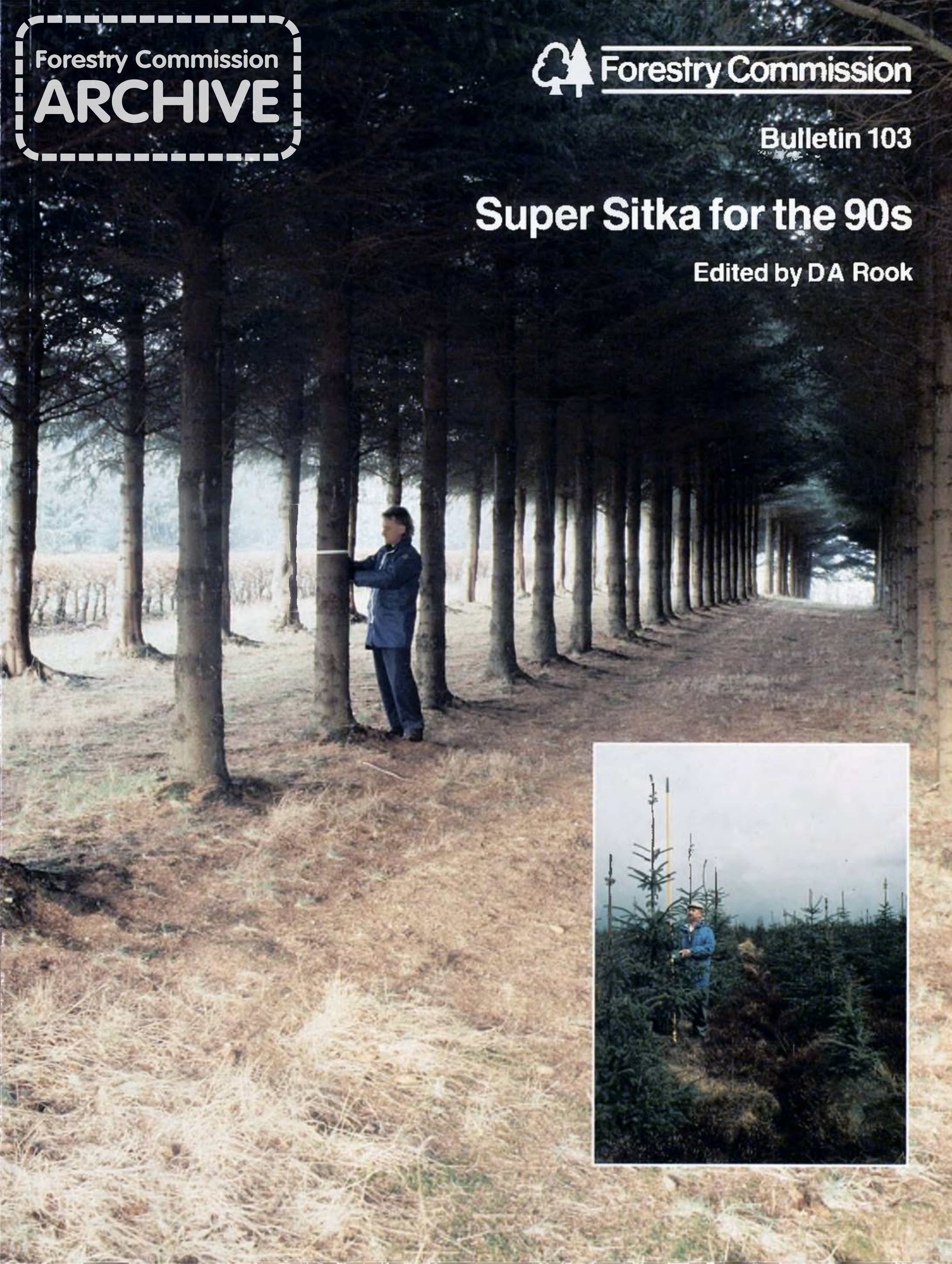
Super Sitka for the 90s

Edited by DA Rook



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Super Sitka for the 90s

Edited by D.A. Rook
Head, Tree Improvement Branch,
Forestry Commission

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Enquiries relating to this publication
should be addressed to:
The Technical Publications Officer,
Forestry Commission, Forest Research Station,
Alice Holt Lodge, Wrecclesham,
Farnham, Surrey, GU10 4LH

Front cover: Fifteen-year-old Sitka spruce growing at Ledmore, Central Scotland. These trees were planted as cuttings in clonal rows and now show similarities in growth and form within each row.

Inset: Measurement of progeny of a vigorous wind-pollinated plus tree.

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Super Sitka for the 90s

Foreword

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is the most important species in upland forestry in Britain and comprises over 50% of current planting. A major pursuit of research on this species has been to increase growth rates and timber yields. This is being achieved by making genetically improved planting stock available to the forest grower. Seed of the most recent intermatings from the tree improvement programme with the greatest potential genetic gain in terms of vigour, health, form and wood properties are always in short supply. Stem cuttings of seedlings are used to multiply up this scarce genetic resource. Currently over 3 million Sitka spruce cuttings are produced and this figure is expected to rise through the 1990s especially as better material becomes available from tree breeding.

The meeting was focused on Sitka spruce in Britain but, to provide a wider perspective, the keynote speaker discussed the use of cuttings in spruce plantations throughout the world. There followed a series of speakers dealing with the following aspects:

- breeding strategy and levels of genetic improvement available;
- vegetative propagation methods;
- silvicultural practices for plantations of cuttings;
- relationship between growth and timber quality;
- increases in volume and revenue from the use of cuttings.

The invited presentations were considered to be of considerable interest to a wider audience and are provided in this Bulletin.

This meeting, which was held near Elgin from 2 to 4 October 1990, was organised by the Forestry Commission Research Division and sponsored by private forestry and forest nursery companies and the Forestry Commission. The attendance was a mixture of nurserymen, forest district officers and managers and forest scientists. The field trip proved most valuable in providing strong visual evidence of some points raised during the talks or discussions.

I wish to thank the speakers and participants at the Elgin meeting. The successful organisation of a meeting inevitably depends on the assistance of a team of persons and acknowledgement should be made to Bill Mason, George Prior, Tony Sharpe and Chris Smith of the Organising Committee, to local Forest District Manager Douglas Clark, and to Silviculture (North) and Tree Improvement Branch staff at Newton Nursery. Lastly, I wish to thank the persons listed opposite who refereed the manuscripts contained in this Bulletin.

David A. Rook
Head of Tree Improvement Branch,
Forestry Commission Research Division

L'Épicéa Sitka Super pour les Années 90

Résumé

L'épicéa Sitka (*Picea sitchensis* (Bong.) Carr.) est l'espèce la plus importante dans les forêts des montagnes de Grande-Bretagne et constitue 50% des plantations courantes. D'importantes recherches ont été faites sur cette espèce afin d'augmenter les taux de croissance et la production de bois. C'est en permettant au sylviculteur d'utiliser des plantes ayant subies des améliorations génétiques que l'on obtient des résultats positifs. On est toujours à court de graines issues des derniers croisements effectués dans le cadre du programme d'amélioration des arbres et qui présentent les plus grandes qualités du potentiel génétique, à savoir vigueur, santé, forme et propriétés du bois. On effectue des boutures de rameau des semis afin de multiplier cette resource génétique rare. On produit environ plus de 3 millions de boutures d'épicéa Sitka et on pense que ce chiffre va encore augmenter dans les années 90 puisque l'on dispose d'un meilleur matériel en matière de reproduction sylvicole.

La conférence tenue à Elgin, en Ecosse, du 2 au 4 Octobre 1990, avait pour objet l'épicéa Sitka en Grande-Bretagne. Cependant, afin d'élargir le débat, le conférencier parla de l'utilisation des boutures dans les plantations d'épicéa à travers le monde entier. Voici les sujets abordés par d'autres orateurs:

- stratégie de reproduction et niveaux d'amélioration génétique disponibles;
- méthodes de propagation végétative;
- pratiques sylvicoles pour les plantations de boutures;
- relation entre croissance et qualité du bois;
- augmentation du volume et des revenus provenant de l'utilisation de boutures.

Ces exposés, reportés dans ce Bulletin, firent naître un intérêt considérable auprès d'un vaste public.

Utilisation des Boutures d'Épicéa dans les Plantations

Le développement historique de la reproduction végétative est succinctement décrit, l'accent étant mis sur les conifères. Les avantages de la reproduction massale et clonale au sein d'un programme de reproduction sont notés. A l'heure actuelle, il y a approximativement 20 millions de boutures d'épicéa réalisées chaque année, la majorité étant effectuée sur l'épicéa commun en Suède, puis vient l'épicéa noir au Canada et enfin l'épicéa Sitka dans les Iles Britanniques.

Les effets de la maturation, de la diversité génétique et de la sylviculture font l'objet de discussions. La propagation en série et en haie constitue les méthodes

principales employées pour retarder la maturation, bien qu'aucune d'entre elles ne puissent l'arrêter complètement. D'autres tentatives ont été faites mais uniquement sur une échelle expérimentale.

La diversité génétique est contrôlée par la composition des familles utilisées et par la composition des mélanges de clones repiqués. Les réglementations en matière d'épicéa prescrivent des mélanges des clones testés allant de 30 clones en Suède à 500 clones en Allemagne. On note la possibilité d'augmenter la diversité génétique par des mélanges de clones.

Les méthodes sylvicoles actuelles utilisent des clones à la fois dans des plantations uniquement constituées des plantes de la propagation végétative, et dans des mélanges avec des semis.

Les plantations monoclonales ne sont pas pratiquées en matière d'épicéa. Actuellement, on obtient, grâce à l'emploi de boutures dans les plantations, un gain de 10 à 20%, comparé à l'utilisation de graines issues des vergers habituels.

Reproduction de l'Épicéa Sitka Amelioré

L'amélioration d'une espèce dépend de la variabilité génétique qui se manifeste dans l'aire naturelle et au niveau de l'arbre individuel. L'épicéa Sitka se développe à des latitudes très larges. On peut constater des différences considérables dans les taux de croissance selon les différentes origines. Les éléments provenant des Iles de la Reine Charlotte s'adaptent au mieux en Grande-Bretagne, mais si l'on vise à augmenter les taux de croissance, mieux vaut alors utiliser d'avantage d'éléments provenant du sud sur les sites protégés des gelées.

L'épicéa Sitka présente un degré de variation élevé à un niveau individuel, mais, en raison d'une héritabilité faible en matière de vigeur, on ne pratique pas la sélection phénotypique à forte intensité. A la base d'un programme qui permet d'identifier les clones destinés à être utilisés dans les vergers commerciaux, on utilise des arbres subissant une moindre sélection quant à la provenance des graines et quant à la réalisation de tests de descendance. Afin de produire des 'mélanges de familles', on pratique la pollinisation contrôlée entre des génotypes supérieurs. Ces mélanges de familles sont multipliés par propagation végétative ce qui maximalise le gain génétique potentiel et minimalise l'intervalle de temps entre l'identification des éléments supérieurs et l'utilisation de stock ayant subi une amélioration génétique dans les plantations commerciales.

Réduire le Coût des Boutures d'Épicéa Sitka

Plus d'un million de boutures d'épicéa Sitka ayant subi une amélioration génétique fut planté en Grande-Bretagne en 1990. Cependant, ces plants coûtent deux à trois fois plus cher que les semis non-ameliorés, ce qui en a réduit la demande. L'analyse montre que l'investissement de main-d'oeuvre dans la production de boutures de second cycle constitue la raison essentielle à ces coûts élevés. De nombreuses techniques alternatives peuvent être mises en place pour réduire ces coûts et améliorer l'enracinement des boutures d'épicéa Sitka. Ces techniques comprennent la propagation dans des conteneurs à semis afin d'éliminer la transplantation, le criblage des boutures avant leur insertion pour maximaliser l'enracinement, la production des plantes-mères à des niveaux d'azote convenables, le stockage réfrigéré afin de pouvoir produire deux récoltes par an, et enfin l'insertion dans des pépinières couvertes pour réduire les coûts de capitaux. Cette analyse préliminaire indique que la mise en oeuvre de ces techniques, partiellement ou dans leur totalité, permettraient de réduire les coûts de production de telle sorte que les prix courants pourraient baisser d'un-tiers.

L'Établissement et la Sylviculture des Boutures de l'Épicéa Sitka

Les lignes directrices sylvicoles actuelles concernant la pratique de boutures d'épicéa Sitka sont mises à jour à la lumière d'un nombre d'expériences récentes effectuées sur les mélanges de provenance et des aspects divers de l'établissement des boutures.

A condition d'utiliser des boutures de premier et second cycle, on peut planter les boutures d'épicéa Sitka transformé soit en mélange par lignes soit en plant simple. Dix ans après leur plantation, des transplants à croissance accélérée provenant des Iles de la Reine Charlote (IRC) étaient 50% plus grands que ceux d'Alaska. La structure de mélange des provenances (alternance des lignes ou alternance des plants dans une même ligne) n'avait aucun impact sur la capacité de survie ou la hauteur. Des boutures et des transplants de la même origine (IRC) avaient la même capacité de survie, étaient de même hauteur et de même diamètre dix ans après. Néanmoins, des boutures de demi-fratrie issues d'une famille ameliorée génétiquement montraient une croissance en hauteur d'environ 10% supérieure à celle des boutures IRC. Quand l'on compara des boutures de demi-fratrie de trois cycles de propagation avec des semis de la même famille et avec des transplants IRC, il s'avéra que les boutures du premier cycle étaient les plus vigoureuses, c'est-à-dire en croissance en hauteur, puis avaient tendance à accuser un léger déclin de vitalité avec le cycle croissant. Une comparaison établie sur des boutures apicales et basales de deux familes révéla des différences considérables entre des familles quant à la hauteur et la forme, mais le type de la bouture avait peu de conséquence.

Les boutures doivent être classées en fonction des normes courantes de qualité des plants, exception faite pour les boutures dont la tige est légèrement plus sinueuse. Cette différence dans la forme de la tige disparaît normalement 1 an ou 2 après plantation. Trois ans après la plantation, des boutures ameliorées issues des pépinières commerciales et expérimentales s'avèrent généralement plus vigoureuses que des transplants IRC. Cependant, un lot de boutures conteneurisées fut sensible aux conditions d'installation, développant une bonne croissance sur un sol cultivé comportant peu de mauvaise herbe, mais croissant plus faiblement sur un terrain délaissé. Généralement, les exploitations sylvicoles standards permettent de constituer et de gérer des plantations de boutures. Néanmoins, elles doivent être plantées sur des sites fertiles présentant un moindre risque de chablis afin que les profits de cette croissance améliorée puissent être maximalisés.

Croissance de l'Épicéa Sitka et la Qualité du Bois

Ce rapport étudie les propriétés de l'épicéa Sitka, particulièrement quant à son exploitation au Royaume Uni pour la fabrication du papier, de la pâte à papier, des panneaux dérivés du bois et du bois de sciage. L'accent est surtout porté sur son utilisation en tant que bois de structure. L'importance des noeuds et du bois de jeunesse est mise en évidence puisque ce sont deux singularités sur lesquelles toute l'attention devrait être portée en matière de génétique et de sylviculture. Des publications sur l'épicéa suggèrent que les arbres qui se sont propagés de façon végétative auraient l'avantage d'une variabilité réduite quant aux propriétés du bois, mais connaîtraient par ailleurs les mêmes problèmes du bois de jeunesse et d'une sensibilité de densité en rapport au taux de croissance que l'on trouve chez les arbres provenant de semis.

Gains Probables en Volume et Revenu par la Plantation d'Épicéa Sitka Amelioré Génétiquement

Tant que les tests de descendance ne sont pas conçus pour produire des résultats significatifs sur une rotation complète, on ne pourra évaluer les gains d'une rotation finale concernant des populations améliorées qu'en extrapolant à partir des données obtenues sur les tests de jeunesse. Les plus anciennes données que l'on a rassemblées à jour pour l'épicéa Sitka dans un test de descendance à pollinisation par le vent révèlent 27 ans en volume, hauteur et diamètre. L'augmentation prévue dans le volume de rotation finale du stock disponible d'épicéa Sitka amelioré est estimée à 15%, ce qui correspond à peu près à un indice de station entier. Les données sont fournies pour montrer la hausse des revenus attribuables à l'exploitation du stock amelioré génétiquement. On s'attend à une augmentation des gains potentiels allant jusqu'à à 25% d'ici à la fin du siècle. Les revenus correspondant à un gain génétique concernant la forme du tronc et la qualité du bois augmenteront de façon positive mais on ne peut pas encore les quantifier.

Super-Sitka für die 90er Jahre

Zusammenfassung

Sitkafichte (Picea sitchensis [Bong.] Carr.) ist die wichtigste Baumart der Hochland-Forstwirtschaft in Großbritannien und stellt 50% der derzeitigen Waldfläche dar. Der Zweck intensiver Forschung über diese Baumart war es, die Wachstumsraten und Holzerträge zu verbessern. Das wird dadurch erreicht, daß dem Förster genetisch verbesserte Pflanzen geboten werden. Samen aus den neuesten Kreuzungen des Züchtungs-programms mit dem besten potentiellen genetischen Gewinn bezüglich Wachstum, Gesundheit, Form und Holzeigenschaften sind immer knapp. Stecklinge von Sämlingen werden verwendet, um diese raren genetischen Ressourcen zu vermehren. Zur Zeit werden über drei Millionen Sitkafichtenstecklinge produziert, und es wird erwartet, daß sich diese Zahl während der 1990er Jahre noch erhöhen wird, besonders wenn aus Züchtungs-programmen besseres Material zur Verfügung steht.

Die Besprechung vom 2. bis 4. Oktober 1990 in Elgin in Schottland konzentrierte sich auf die Sitkafichte in Großbritannien. Um aber eine breitere Perspektive zu bieten, befaßte sich der Hauptredner mit der Verwendung von Stecklingen in Fichtenanpflanzungen auf der ganzen Welt. Eine Reihe von Sprechern behandelten daraufhin die folgenden Aspekte:

Züchtstrategie und die Ebenengenetischer Variation;
Vegetative Vermehrungsmethoden;
Waldbauliche Praktiken für Stecklingskulturen;
Beziehung zwischen Wachstum und Holzqualität;
Erhöhung des Volumens und der Einnahmen durch den Gebrauch von Stecklingen.

Man war der Ansicht, daß die vorgeschlagenen Beiträge von großem Interesse für ein breites Publilkum sein könnten, und sie werden in diesem Bericht veröffentlicht.

Die Verwendung von Fichtenstecklingen für Pflanzungen
Die historische Entwicklung der Vegetationsvermehrung wird kurz beschrieben, mit Betonung auf Nadelbaumarten. Die Vorteile von Massen-und Klonvermehrung in einem Züchtprogramm werden aufgeführt. Zur Zeit werden jährlich ca. 20 Millionen Fichtenstecklinge produziert; den Hauptanteil stellt Fichte in Schweden dar, dann Schwarzfichte in Kanada und Sitkafichte auf den britischen Inseln.

Die Auswirkungen der Alterung, der genetischen Vielfalt und der Wald-

bautechnik werden behandelt. Heckenpflanzung und Serienvermehrung sind die hauptsächlich angewandten Methoden zur Verzögerung des Alterungsprozesses, obwohl keine von ihnen die Alterung ganz verhindern kann. Andere Ansätze wurden zwar versucht, scheinen aber nur von experimenteller Bedeutung zu sein.

Die genetische Vielfalt wird durch die Zusammensetzung der verwendeten Familien gesteuert sowie durch die Zusammensetzung ausgepflanzter Klonmischungen. Die Bestimmungen für Fichte verlangen Klonmischungen, die aus geprüften Klonen bestehen. Diese reichen von 30 Klonen in Schweden bis zu 500 Klonen in Deutschland. Die Möglichkeit die genetische Vielfalt durch Klonmischungen Zu erhöhen, wird beschrieben.

Derzeitig Klonen werden in reinen Kulturen von vegetativ vermehrtem Material verwendet sowie solche, die mit Sämlingen vermischt sind.

Einklonkulturen werden bei Fichte nicht verwendet. Im Vergleich zum Gebrauch von Samen aus bestehende Samenplantagen beim Gebrauch von Fichtestecklingen Gewinne von 10-20% erzielt.

Züchten verbesserter Sitkafichten

Die Verbesserung einer Baumart hängt von der Höhe der genetischen Variabilität ab, die in der Natur auf Einzelbaumniveau besteht. Sitkafichte hat eine weite natürliche Verbreitung, und große Unterschiede in der Wachstumsrate zwischen Bäumen von verschiedenen Herkünften. Material aus den Queen-Charlotte-Inseln ist für Großbritannien am besten angepaßt, obwohl eine Verbesserung der Wachstumsrate erreicht werden kann, wenn Bäume von weiter südlich gelegenen Herkünften auf Standorten angepflanzt werden, die keine Probleme mit Frost haben.

Sitkafichte weist auf Einzelbaumniveau große Unterschiede auf, aber wegen der niedrigen Erblichkeit der Wuchseigenschaften wird hier keine hochintensive phänotypische Auswahl getroffen. Eine niedrigere Intensität bei der Wahl der Baumkandidaten innherhalb bekannter Samenquellen bildet zusammen mit der Nachkommenschaftsprüfung die Basis des Programms zur Identifizierung von Klonen, die in kommerziellen Samenplantagen verwendet werden sollen. Eine gelenkte Kreuzung zwischen überlegenen Genotypen wird zur Produktion von 'Familienmischungen' angewandt. Sie werden vermehrt, durch vegetative Fortpflanzung um maximale potentialle genetische Gewinne zu erzielen und um die Verzögerung zwischen der Identifizierung überlegenen Materials und dem Gebrauch von genetisch verbesserten Pflanzen in der kommerziellen Forstwirtschaft auf ein Minimum zu beschränken.

Die Reduzierung der Kosten von Sitkafichtenstecklingen

Über eine Million genetisch verbesserter Sitkafichtenstecklinge wurden 1990 in Großbritannien angebaut. Diese Pflanzen kosten jedoch zwei- bis dreimal so viel wie nicht verbesserte Sämlingpflanzen, was einen Rückgang des Bedarfs zur Folge hatte. Die Analyse zeigt, daß der Arbeitsaufwand bei der Produktion von Stecklingen ein bedeutender Grund für diese hohen Kosten ist. Eine Reihe von alternativen Methoden kann angewandt werden, um die Kosten zu reduzieren und die Bewurzelung der Sitkafichtenstecklinge zu verbessern. Diese Methoden sind u.a. die Vermehrung in Containern, wodurch ein Umpflanzen vermieden wird, die Überprüfung von Stecklingen vor dem Stecken, um die Bewurzelung zu maximieren, die Mutterbaumpflege, um einen ausrechenden Stickstoffgehalt zu gewährleisten, die Gefrieraufbewahrung, um zu ermöglichen, daß jährlich zweimal produziert wird, und das Einsetzen in abgedeckten Gartenbeeten, um die Kapitalkosten zu verringern. Eine vorbereitende Analyse deutet an, daß die Anwendung einer oder mehrerer dieser Methoden dabei helfen könnte, die Produktionskosten zu reduzieren, wodurch die derzeitigen Preise bis zu einem Drittel verringert werden könnten.

Etablierung und Waldbau von Sitkafichtenstecklingen

Bestehende waldbauliche Richtlinien zum Gebrauch von Sitkafichtenstecklingen werden vor dem Hintergrund einer Reihe von kürzlich durchgeführten Experimenten mit Herkunftsmischungen und verschiedenen Aspekten der Etablierung von Stecklingen erneut überprüft.

So lange Erst- oder Zweitzyklusmaterial verwendet wird, können verbesserte Sitkafichtenstecklinge rein oder in reihenweiser Mischung angepflanzt werden. Zehn Jahre nach dem Anpflanzen waren die Verschulpflanzen der schneller wachsenden Herkünften aus den Queen-Charlotte-Inseln (QCI), 50% höher als jene aus Alaska. Das Muster der Herkunftsmischung (abwechselnde Reihen oder abwechselnde Pflanzen innerhalb einer Reihe) hatte keine Auswirkung auf das Überleben und den Höhenwuchs. Stecklinge und Verschulpflanzen derselben QCI-Herkunft hatten nach 10 Jahren eine ähnliche Überlebensrate, Höhe und Durchmesser. Halbgeschwisterstecklinge einer genetisch verbesserten Familie wiesen jedoch ein um 10% besseres Höhenwachstum als die QCI-Pflanzen auf. Wenn man Halbgeschwisterstecklinge von drei Vermehrungsszyklen mit Sämlingen derselben Familie und mit QCI-Verschulpflanzen verglich, wurde deutlich, daß Erstzyklusstecklinge das stärkste Höhenwachstum aufwiesen. Diese Vitalität verringerte sich leicht bei darauffolgenden Zyklen. Ein Vergleich zwischen Triebspitzen- und Triebfußstecklingen von zwei Familien verdeutlichte bedeutende Unterschiede zwischen den einzelnen Familien und zwar in Größe und Form, was aber wenig von der Art der Stecklinge abhing.

Stecklinge sollen nach den normalen Pflanzenqualitätsstandards sortiert werden, gewisse Zugeständnisse sollen jedoch für eine etwas gekrümmtere Stammform bei den Stecklingen gemacht werden. Dieser Unterschied in der Stammform verschwindet normalweise innerhalb von 1 bis 2 Jahren nach dem Auspflanzen. Drei Jahre nach dem Auspflanzen sind verbesserte Stecklinge aus Forschungs- und kommerziellen Baumschulen normalweise stärker als QCI-Verschulpflanzen. Containerisierte Stecklinge erwiesen sich Etablierungsbedingungen gegenüber jedoch als empfindlich: gutes Wachstum auf kultiviertem Boden mit minimalen Unkrauteinflüssen aber schlechteres Wachstum und eine niedrigere Überlebensrate auf einem nicht kultivierten Standort mit starken

Unkrauteinflüssen. Allgemein gesehen können standardmäßige waldbauliche Praktiken bei der Begründung und Bewirtschaftung von Stecklinganpflanzungen angewandt werden. Sie sollen jedoch auf fruchtbaren Standorten mit niedrigem Windwurfrisiko angepflanzt werden, damit die Vorteile einer verbesserten Wachstumsrate maximiert werden können.

Das Wachstum der Sitkafichte und die Holzqualität

Dieser Bericht befaßt sich mit den Eigenschaften der Sitkafichte bezüglich ihrer Verwendung bei der Zellstoff- und Papierherstellung, bei der Herstellung von Holzwerkstoffplatten und als Sägeholz in Großbritannien. Besonders betont wird der Gebrauch als Bauholz. Die Wichtigkeit von Quirlen und juvenilem Holz werden als die zwei Eigenschaften besonders hervorgehoben, auf die sich die waldbauliche und genetische Aufmerksamkeit richten soll. Veröffentlichungen über Fichte deuten an, daß vegetativ vermehrte Bäume den Vorteil einer verringerten Variabilität der Holzeigenschaften haben können; sie weisen jedoch auf dieselben Probleme von Jugendholz und Abhängigkeit von Dichte zu Wachstumsrate hin, die in Bäumen aus Samen auftreten.

Wahrscheinliche Zunahmen von Volumen und Einkommen durch die Anpflanzung von genetisch verbesserter Sitkafichte

Wenn Nachkommenschaftsprüfungen nicht so angelegt sind, daß sie bedeutungsvolle Ergebnisse bis zum Umtriebsalter erbringen, muß die Kalkulation der wahrscheinlichen Gewinne beim Umtriebsalter aus verbesserten Produktionspopulationen auf der Extrapolation von Daten aus Jugendtests basieren. Die ältesten bisher gesammelten Daten in einer windbestäubten Nackkommenschaftsprüfung von Sitkafichten waren Volumen, Höhe und Durchmesser von 27 Jahren. Die vorausgesagte Erhöhung des Umtriebsvolumens von derzeitig erhältlichen, verbesserten Sitkafichtenpflanzen wird auf 15% geschätzt, was ungefähr das Äquivalent einer vollen Bonität darstellt. Daten werden angegeben, die die Erhöhung des Einkommens aufzeigen, das auf den Gebrauch genetisch verbesserter Pflazen zurückzuführen ist. Es wird erwartet, daß potentielle Gewinne bis zum Ende des Jahrhunderts auf 25% angestiegen sein werden. Eine Erhöhung des Einkommens durch genetischen Gewinn bei der Stammform und Holzqualität wird postiv sein, kann jedoch noch nicht quantifiziert werden.

Paper 1

Use of spruce cuttings in plantations

*J. **Kleinschmit**, Lower Saxony Forest Research Institute, Department of Forest Tree Breeding, D-3513 Escherode, Germany.*

Abstract

The historical development of vegetative propagation is briefly described with emphasis on coniferous species. The advantages of bulk and clonal propagation in a breeding programme are noted. At present approximately 20 million spruce cuttings are produced each year, the majority being of Norway spruce in Sweden followed by black spruce in Canada and Sitka spruce in the British Isles.

The effects of maturation, genetic diversity and silviculture are discussed. Hedging and serial propagation are the main methods used to delay maturation, although none of these can stop maturation completely. Other approaches have been tried but appear to be only of experimental importance.

Genetic diversity is controlled by the composition of families used and by the composition of clonal mixtures planted out. The regulations for spruce prescribe clonal mixtures of tested clones ranging from 30 clones in Sweden to 500 clones in Germany. The possibility of increasing genetic diversity by clonal mixtures is noted.

The present silvicultural approaches use clones both in pure plantations of vegetatively propagated material and in mixtures with seedlings. Monoclonal plantations are not used in spruce. At present use of spruce cuttings in plantations achieves gains of 10-20%, compared with the use of seed from current orchards.

Introduction

Vegetative propagation is a natural phenomenon in many species, e.g. poplars, willows, cherry, aspen, and has been used by man for many centuries. Pliny (76) described methods of air layering and the first report of cutting propagation is given in the Bible (Ezekiel 17, verses 22–24).

Poplars and willows have been vegetatively propagated throughout recorded history and the coniferous species, *Cryptomeria japonica*, has been vegetatively reproduced by cuttings in Japan for at least 500 years. The first record of Norway spruce cuttings being rooted was by Pfifferling in 1830. Since then many species have been successfully propagated vegetatively and active research to provide enhanced rooting has been encouraged as the material is suitable for work on detection and synthesis of plant hormones.

With the production of genetically improved material from tree breeding programmes, rapid methods of propagation became essential in order to produce adequate supplies of improved material in commercial quantities. Poplar breeding made rapid progress since vegetative propagation of superior individuals is simple. The use of clones however was not regulated and monoclonal plantations were the rule. In most other species propagation of young plants was possible, but reduced rooting and growth occur with older material and so maturation effects are a serious problem. Although many attempts have been made to improve propagation methods of mature 'plus trees', success has been very limited (see proceedings of a meeting held in Rotorua, New Zealand on vegetative propagation and reported in the *New Zealand Journal of Forestry Science* **4,** 1974).

The aim of most forest tree breeders at that time was still to propagate mature trees. The role of vegetative propagation was reconsidered bearing in mind that although old trees are tested, their genetic acceptability for inclusion in the breeding population is judged according to the performance of young trees. Consideration was therefore given to the use of young trees directly for propagation, thus avoiding the problems of maturation.

There followed a new wave of intensive research into vegetative propagation, and several important meetings were held from 1976 to 1982 and reported as follows: *Acta Horticulturae* (1976), Institute for Tree Breeding, Uppsala (1977, 1981), Association Forêt Cellulose (1982), Department of Forest Tree Breeding, Lower Saxony Forest Research Institute (1982), and Abbott and Atkin (1987). Many temperate tree species have been included in this research. Today probably more than 200 million trees are vegetatively propagated annually, of which roughly 60 million are conifers (Talbert, Ritchie and Gupta, 1990). Of these, 30 million are *Cryptomeria japonica* cuttings, more than 10 million are *Pinus radiata* cuttings and *in vitro* propagated plants and nearly 20 million are spruce species (Bentzer, 1990). *Pseudotsuga menziesii*, *Chamaecyparis* spp., *Pinus taeda* and *Larix* spp. are only propagated in small quantities.

Advantages of vegetative propagation

There are a number of good reasons to use vegetative propagation in forestry, especially in combination with tree breeding programmes.

- Genetic gain for growth and quality traits can be quickly and efficiently used without loss due to recombination. This improves flexibility of a breeding programme and the transfer of results to commercial practice.
- Clones can be produced with highly specific properties, e.g. special wood characterstics such as high basic density combined with vigorous growth for commercial plantations, Christmas tree characteristics for specialised markets, high tolerance against salt and pollution for urban plantations, and with late flushing or early bud set for specific environments such as frosty sites.
- Genetic gain can be exploited without dependance on flowering, which saves about 15 years in the case of Norway spruce.
- Subdivisions of breeding zones can be matched with clonal characteristics with greater success than with seedlings.
- Species which are generatively difficult to propagate (Dipterocarps) or which flower irregularly (beech, oak) can be handled more easily in breeding programmes.
- Rare, expensive seed can be germinated and bulked up by cuttings and thus used commercially.
- By the selection of appropriate material and using vegetative propagation, relatively homogeneous commercial stands can be obtained.
- Control of genetic and phenotypic diversity is easier than with generative propagation as genetic variation can be narrowed down or expanded.
- According to the type of plantation one can utilize complementary clonal behaviour, e.g. rows of slow growing clones alternating with fast growing clones to predetermine later silvicultural treatments, mixes of clones and seedlings, 'correlation breakers', i.e. clones which do not show up negative correlations of desired traits as compared to the base population, or even pure one-clone plantations.
- For certain species physiological rejuvenation appears possible, but it depends on the method of vegetative propagation, as it is more commonly successful with *in vitro* propagation methods, for example with cherry and birch. Progress in somatic embryogenesis with flower tissue shows that even mature trees can be completely rejuvenated (Joergensen, 1989), providing new possibilities for clonal selection and propagation.

Disadvantages of vegetative propagation

Nevertheless, there are problems connected with vegetative propagation. These can be classified into biological problems (maturation, loss of genetic diversity, rank changes, clone-identification), managerial problems (cost per propagule, risk considerations, percentage of clonal forestry), technical problems (propagation technique, mechanisation, mixing of clones or families) and ethical problems (conservation of natural variability, manipulation of nature).

- Major biological problems are the loss of genetic diversity with uncontrolled use of vegetative propagation, the decrease of rooting potential with maturation, rank changes of clonal growth with age or with growing site which are more obvious than those between generatively produced populations, and identification problems which become more severe with increasing numbers of clones.
- Managerial problems are less severe than biological problems, but they can restrict the practice of vegetative propagation. Cost per propagule is often higher than with comparable seedling plants, but this can be justified by a higher genetic gain. Production risk is in many species difficult to estimate due to lack of experience; it is dependent on the genetic diversity at the time of use of the vegetatively propagated material, and on the percentage of forests which are replanted with vegetative propagules.
- Technical problems usually diminish with increased experience. Propagation techniques have been considerably improved, and the degree of mechanisation increased. Mixing of clones may be carried out either directly before rooting or before transplanting to the forest.
- There is increasing ethical concern against the manipulation of nature. This is partly a rather diffuse feeling, but it may have biological roots such as the conservation of natural variability. These concerns should be taken seriously, and balanced against the obligation to provide future generations with sufficient raw material. This has been discussed elsewhere (Kleinschmit, 1989).

Present state of spruce cutting propagation

Spruce breeding programmes based on conventional seed orchard methods are long term and depend on the vagaries of climate: under central European conditions it is 20 to 30 years before reasonable crops can be expected. This was one motivating factor encouraging intensive work with vegetative propagation in spruce species; other factors were realisation of extra genetic gain, higher flexibility in the programmes, more rapid exploitation of genetic gain, the potential of more homogeneous planting stock and better matching of genotypes to sites. To indicate the sizes of the majority of these programmes, Bentzer (1990) cites numbers of cuttings inserted annually – Norway spruce (*Picea abies*) (Scandinavia *ca.* 8 million, Western Europe 2.2 million, Eastern Europe 1.0 million, Canada 0.1 million), black spruce (*Picea mariana*) (Canada 4.1 million), and Sitka spruce (*Picea sitchensis*) (British Isles 3.8 million). Some, including the majority of the Norway spruce programmes are based on clonal selection and testing; the biggest is the Hilleshøg programme in Sweden with 4 million cuttings produced annually, followed by the National Board of Forestry in Sweden with nearly 2 million cuttings, the German programmes with 1.5 million plants, the Norwegian programme with 1.2 million plants, and the French programme with 1.0 million plants.

Technically the most advanced production is by Hilleshøg in Sweden (Bentzer, 1990), where all cuttings are rooted and delivered in containers. The rooting houses are highly automated and close to optimal. The clones are maintained in hedges and at the same time used for further breeding.

Most of the other Norway spruce programmes are working with bare root plants, rooted in technically simpler greenhouses and transplanted to ordinary nursery beds. The Norwegian programme uses bulk propagation from controlled crosses or open pollination of selected families only. Some of the programmes (e.g. Finland and Denmark) combine bulk propagation of families with propagation of specific clones.

The black spruce programmes in Canada are based on bulk propagation of rare seed of various origins of predominantly tested material. The plants are produced in containers and the stock plants are hedged.

The Sitka spruce programmes bulk propagate scarce seed with a multiplication factor of 500 to 1000 plants per seed for fast production of improved stock using bare root plants.

Differences in the programmes are variously due to species, to different control of maturation and to genetic diversity, and to local breeding and silvicultural situations. These will be discussed in more detail below.

Handling of maturation

Maturation is the main obstacle for any programme of clonal propagation; it is defined as the development of increasing size, complexity and differentiation with age during ontogenesis leading to sexual reproduction (mature phase). This process is associated with morphological, physiological, and biochemical changes and with differential gene activities. Maturation is reflected in decreasing rooting ability (Figure 1.1), poorer root systems, longer duration of plagiotropic growth habit and slower initial growth (Meier-Dinkel and Kleinschmit, 1990).

The easiest escape from this problem is bulk propagation of juvenile seedlings. This, however, is a dead end, since it only leads to a production population without further improvement. Where rapid transfer of superior, tested material is required, clonal propagation and testing need methods which exclude or at least diminish the maturation effects. Two systems are used in spruce:

1. Hedging

Hedging is the repeated shearing of trees close to the ground. The chronologically oldest parts of trees, close to the root collar, are physiologically the most juvenile. Experiments with coniferous species show that hedging can slow down maturation considerably. It is therefore used in some programmes (Denmark, Hilleshøg/Sweden, Canada), and has the advantage that the clones can be collected, continuously used and extended to the numbers needed. The disadvantage is the fact that hedging orchards have to be maintained solely for the propagation of cuttings; selected clones are either accompanied by gaps in the orchard or by rejected clones maintained but no longer needed. Rooting experiments with old Norway spruce hedges have shown that maturation cannot be arrested completely by hedging.

2. Serial propagation

Serial propagation, i.e. repeated repropagation of cuttings starting at a young age, is another way of reducing maturation effects. This sytem has so far been repeated up to the 7th propagation cycle in Norway spruce with 3 years per cycle. Age from seed is 22 years

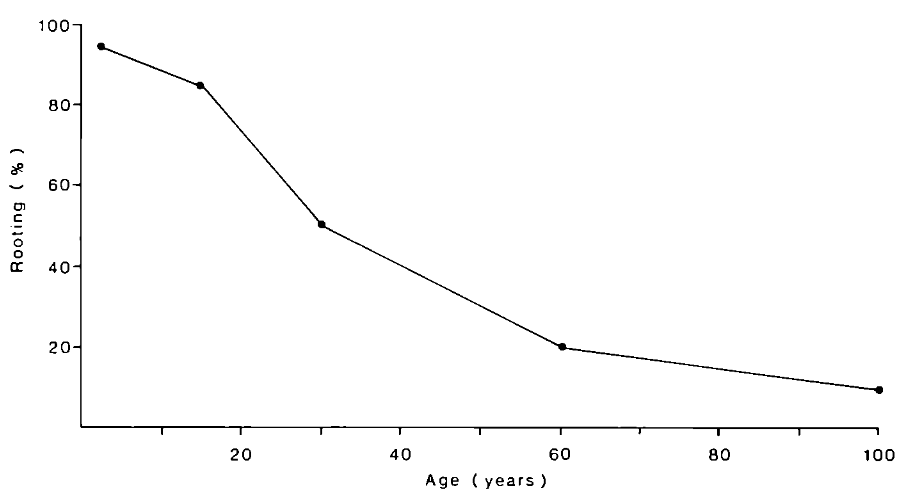

Figure 1.1 Decrease of rooting ability of Norway spruce clones with age. (Average of 20 clones per age class. Data from Lower Saxony Forest Research Institute, 1969.)

[4-year-old seedlings for first propagation cycle and 6 × 3 = 18 years up to the 7th cycle] (Robertson and Kleinschmit, submitted for publication). There was no significant reduction in rooting percentage and only slight changes in different morphological traits observed (Figure 1.2). Thus although rates of maturation are reduced, they are not stopped and sometime in the future rooting of the material may not be possible. Since 10 to 15 years is required for clonal selection and testing in Norway spruce, maturation effects cannot be eliminated even with serial propagation.

Advantages of serial propagation are: no separate clone archives have to be maintained and selection of clones is easy, since only reselected clones are repropagated. Disadvantages of serial propagation are: clones can be repropagated only in cycles of 3 years,

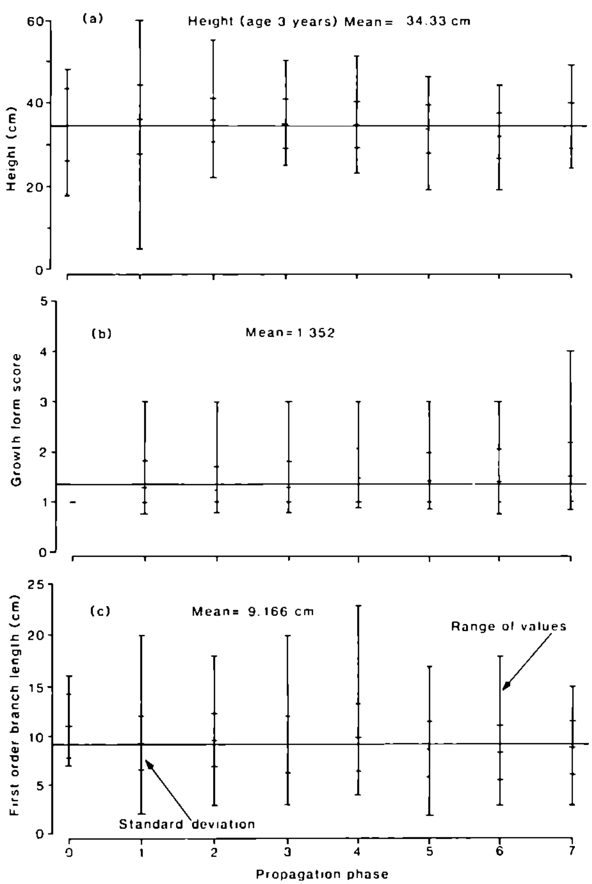

Figure 1.2 Effect of serial propagation of Norway spruce on: (a) height, (b) growth form, and (c) branch length.

although this could be changed by introducing a limited period of hedging at the beginning. Plants despatched for planting are also used for taking cuttings, which may cause problems with some customers.

Both systems allow the reintroduction of selected superior clones into the next breeding cycle at an advanced age, when maturation sets limits to clonal repropagation. This can be one aim of the programme, e.g. the Hilleshøg system where juvenility is maintained in a hedging orchard and maturation is attained by flower induction techniques.

It can also be one result of the development of the clonal tests, as is planned in the Lower Saxony programme. As soon as the clones reach flowering age at around 20 years, the clonal tests are converted to clonal seed orchards after an intensive reduction of clone numbers to the best 20% in the test. At the same time these superior clones are combined in a single pair mating design for production of the next base population for selection. At this stage both options, i.e. bulk propagation and clonal selection and testing are again open.

Different methods of rejuvenation such as repeated regrafting or heavy shearing of adult trees have been tested with spruce by Franclet (1982), in France, but no real success has been attained. Somatic embryogenesis with diploid flower tissue has not yet been successful with conifers. However, this seems to be a promising approach to the maturation problem. If this were successful, the clonal option could be carried on even with old clones tested intensively under different environments.

Handling genetic diversity

Genetic diversity of clonal forestry can vary between the extremes of monoclonal plantations and an increase of diversity compared with conventional seedling forestry. In natural populations three levels of diversity exist:

between populations (provenances) of a species;

between individuals within populations;

within individuals (degree of heterozygocity).

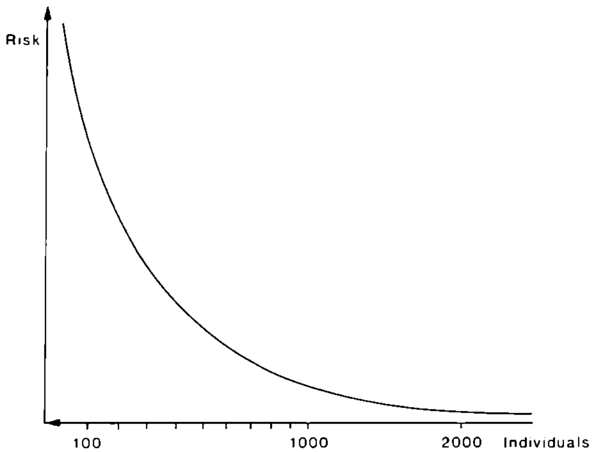

Figure 1.3 Relationship between risk and numbers of unrelated individuals in a population. Theoretical curve based on limited amount of experimental evidence available.

In spruce species a considerable amount of variation is found between individuals within populations (Kleinschmit, 1987). There is theoretically an inverse relationship between genetic diversity and risk (Figure 1.3). It is however disputed where the limits of unacceptable risk start and where risk equals risk in seedling forestry. Libby (1982) argues that quite limited numbers of clones (less than ten) may be safer than seedling populations. Huehn (1985; 1986a, b, c; 1987) shows from theoretical studies that 30-50 clones may be sufficiently safe, and practical experience shows that even monoclonal plantations may be safe in some species such as *Cryptomeria japonica*.

Different influences have to be taken into account in deciding how far genetic variation can be restricted (Figure 1.4). A major tree species handled in a breeding population needs more clones than a minor tree species in a production population in limited plantations. Long testing periods and short time of application justify a more narrow base than short testing and long time of application. In short rotation species planted in a homogeneous environment, like poplars, reduced clone numbers can be more easily justified than for a long rotation species like oak planted under heterogeneous site conditions. In most spruce programmes, alternative propagation methods are used besides vegetative propagation. Seed harvested from stands and seed orchards are used as well, which increases genetic diversity, and breeding populations exist in addition to production populations. Since spruces are planted extensively

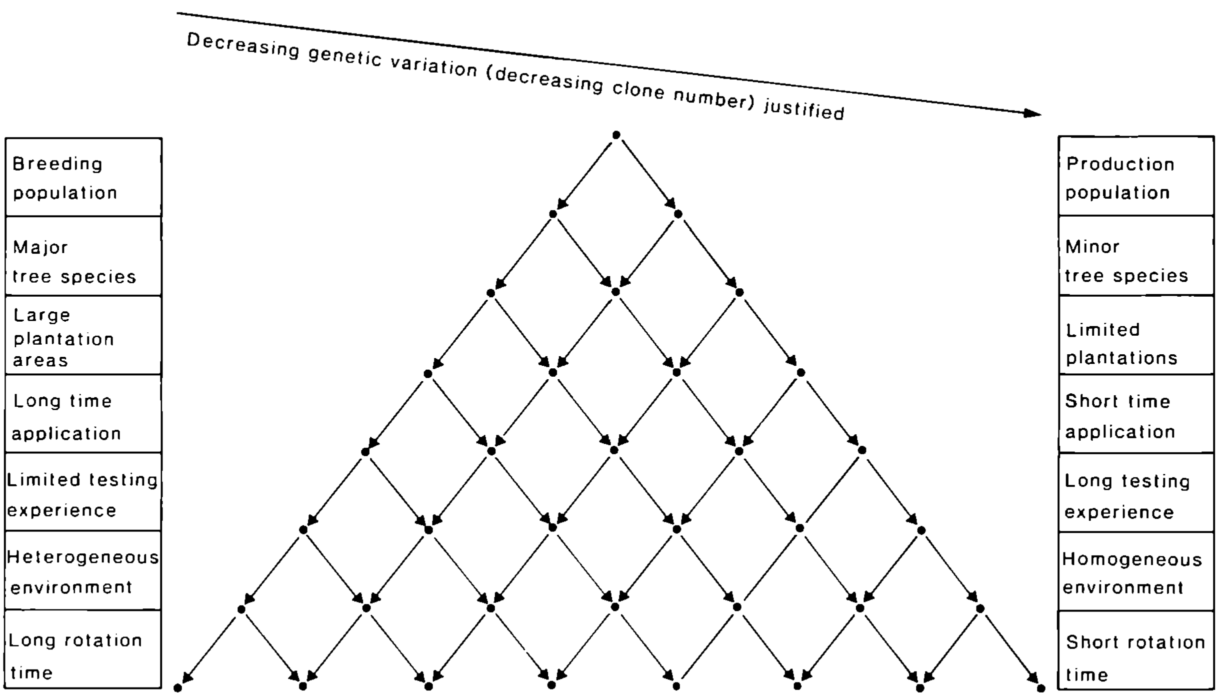

Figure 1.4 Factors affecting optimal numbers of clones in a mixture.

Table 1.1 Swedish regulations for use of clonal material

Testing				*Commercial use*	
Test level	*Duration (years)*	*Minimum number of test sites*	*Minimum number of replications*	*Minimum number of clones/mixture*	*Maximum number of ramets/clone*
1	6	2	5	120	250 000
2	9	4	7	60	750 000
3	12	6	7	30	1 500 000

in large plantations with heterogeneous environments, a certain level of diversity should be maintained. The fact that vegetative propagation has not been used on a wide scale for a long time, and that testing experience is limited when compared with rotation length, point in the same direction.

Bulk propagation does not generally reduce genetic diversity as strictly as clonal propagation, although it can be quite drastic if only a single controlled cross is reproduced. For clonal application different rules have been developed. The Swedish rules, which are currently under re-evaluation, combine intensity and duration of testing with the minimum number of clones needed (Table 1.1); this is biologically sound.

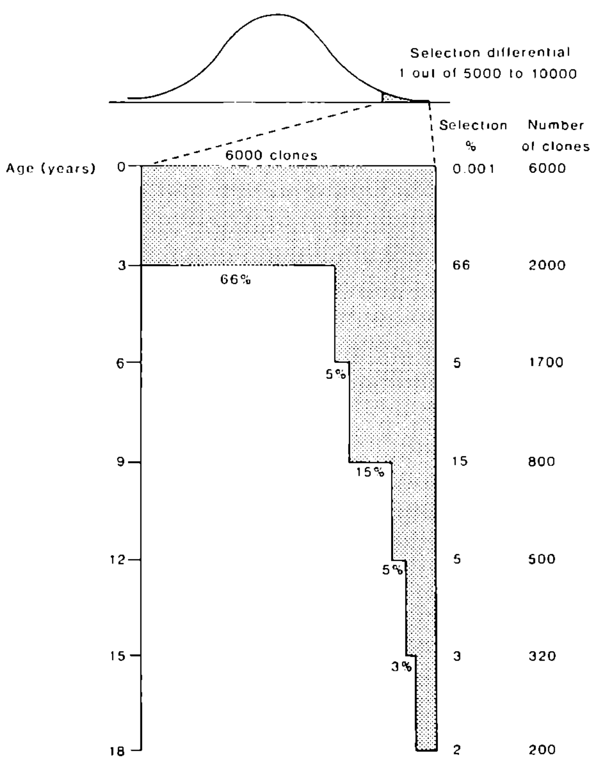

Figure 1.5 Proposed selection programme for Norway spruce clones at the Lower Saxony Forest Research Institute.

German regulations prescribe a minimum number of 500 clones in a clonal mixture for a major species such as Norway spruce which is planted widely and 100 clones for specific application, such as sites prone to late frosts, or to pollution. Since clonal selection is carried out sequentially, clonal numbers decrease with time. As testing information increases, clones are rejected and so the composition of clonal mixtures changes over time. The number of plants per clone increases in parallel with the reduction of clone numbers. The example of the Norway spruce selection programme of the Lower Saxony Forest Research Institute is given in Figure 1.5. Outstanding seedlings are selected from tested provenances with a selection intensity of 1 : 5000 to 1 : 10 000. At the end of the nursery stage two-thirds of the total number of clones are rejected on the criteria of health, growth and survival. The best clones are planted in three field experiments with seven replications each as single tree plots. The subsequent selections are much less intensive and parallel the 3-year propagation cycles. At present the number of plants per clone used in commercial propagation does not exceed 2000, which is similar to the situation of bulk propagation with Sitka spruce, where 500 to 1000 cuttings are produced per seed.

Genetic diversity can be increased to levels comparable with those of seedling populations by using clones originating from different, divergent base populations. Svolba (1988) demonstrated that genotypic diversity was greater in a clonal mixture originating from three different base populations than in progenies originating from a seed orchard or from a seed stand. The degree of diversity can be controlled by combining clones of known characteristics.

Silvicultural aspects

Monoclonal plantations are not used in spruces although they are the rule for poplars and *Cryptomeria*. At present either artificial clonal mixtures or 'natural' clonal mixtures (bulk propagated material) are used. The bulk systems use mostly mixtures of different families. The clonal systems use either intimately mixed clones or clonal mini-mosaics. The numbers of clones currently used in mixtures range from 30 to 5000. The Hilleshøg system uses units of 40 plants per clone in rows corresponding to 40 plants in a container block; the number of clones corresponds to the Swedish rules.

In Germany 500 to 5000 clones are used in mixtures. The unrooted cuttings of these clones are thoroughly mixed before insertion for commercial propagation; only in the breeding programme is clonal identity maintained.

Silvicultural practice uses both pure plantations of vegetative propagules and mixtures of seedlings with cuttings. The decision on the best option largely depends on the price per propagule in relation to seedling plants. With higher prices per cutting (the price differential is currently 30 to 100% higher) – it is desirable either to mix the valuable vegetative material with seedlings, as is done in some of the Sitka spruce programmes and as was initially done in some of the Norway spruce programmes, or to use reduced plant numbers, which is justified with preselected clones or families. A reduction of 25% of the plant numbers per hectare actually compensates for the higher price of Norway spruce cuttings in Germany. Such a solution is easier from a management point of view. In silvicultural systems with natural regeneration, e.g. beech in Germany, enrichment planting with high yielding spruce clones is another alternative involving little risk.

These approaches make the basic assumption that vegetative propagules are superior in growth and/or quality to seedlings. The oldest programmes are over 20 years old so that first estimates of potential gain are possible. From clonal tests we know that an intensive early selection as given in Figure 1.5 can result in a gain for height growth at age 20 of 10–20%. The most outstanding clones may exceed this gain by a further 30%, although this superiority cannot be completely realised in clonal mixtures designed to diminish risk. In a study with 17-year-old clonal material, the realised gain for height was 9%, for diameter 24% and for individual tree stem volume 70% (Kleinschmit and Svolba, 1991). Similar gains have been obtained in programmes with Norway spruce in Denmark and Sweden. Rank changes occur between clones within the first years and are especially pronounced in plantations on climatically het-

Figure 1.6 The effect of number of clones on changes in correlations and differences between group mean height for Norway spruce.

erogeneous sites. Usually the best clones are more stable than average clones, which may be due to higher degree of heterozygocity. The older Norway spruce clones under test have now reached an age of 45 years; no significant rank changes took place after age 20.

The relationship between the selected number of clones in a mixture following ranking in early selection, the reliability of early selection information, and genetic gain is given in Figure 1.6. Age-age correlations increase dramatically with the numbers of clones included in a group. At the same time genetic gain (group mean differences) decreases to values between 20 and 10%. It is obvious that clonal mixtures of 30–40 clones are quite stable in their performance and already predictable at an age of 3 years. However, gain decreases drastically for mixtures as compared to a single clone, although this gain is more secure. On the other hand these gain estimates are conservative due to the fact that less vigorous clones can be eliminated by thinning during stand development; for example the final crop of Norway spruce in Germany is only 10% of the original number planted. This is one significant advantage for forest tree breeding, since natural selection under the respective growing conditions can support human selection activities. By choosing clone or family composition which covers a broader ecological framework an artificial population can be adjusted to the local situation by natural selection.

By improving propagation conditions, the price difference between vegetative propagules and seedlings can be reduced further. This will change the silvicultural concepts to some extent. The programmes of vegetative propagation in Germany, Sweden and France are approaching between 15 and 50% of the total plantation programmes. In private forestry, 50% with the greater dependence on economic return is more probable, while in public forestry with a higher percentage of natural regeneration 25 to 35% is likely in the near future. In the long term the figures may be higher, or lower, depending on the success of the earlier plantations. The most fertile sites will be allocated to the most valuable material. Sufficient areas will be available for conventional seedling forestry and thus for conservation of additional genetic variation outside the breeding programmes.

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Paper 2

Breeding improved Sitka spruce

A.M. Fletcher, Tree Improvement Branch, Forestry Commission, Northern Research Station, Roslin, Midlothian, EH25 9SY, UK.

Abstract

Improvement of a species depends on the amount of genetic variability which is exhibited across its natural range and at the individual tree level. Sitka spruce has a wide latitudinal distribution and large differences in growth rate are found among different origins. Material from the Queen Charlotte Islands is the best adapted for use in Britain but increases in growth rate can be obtained by using more southern origins on sites where there are no problems with frost.

Sitka spruce shows a high degree of variation at the individual tree level but, due to low heritability for vigour characters, high intensity phenotypic selection is not practised. A lower intensity of selection of candidate trees within known seed sources combined with progeny testing forms the basis of the programme to identify clones to be used in commercial seed orchards. Controlled pollination amongst superior genotypes is used to produce 'family mixtures'. These are multiplied by vegetative propagation to utilise the maximum potential genetic gain and to minimise the time lag between identification of superior material and the use of genetically improved stock in commercial forestry.

Introduction

Tree improvement is a combination of silviculture and tree breeding aimed at producing higher quality products. The tree breeding contribution consists of producing a specially desired genotype but it cannot fulfil its potential unless appropriate silvilcultural treatments are implemented. No improvement can be made by the tree breeder unless there is sufficient genetic variability. In general, tree species possess greater variability than many agricultural plant species (Hamrick, Metton and Linehart, 1979), and it is essential to maintain this genetic variability both within wild populations and in the 'breeding populations' being developed. There are three levels of genetic variability which the tree breeder can utilise, namely:

- species level;
- provenance or seed origin level;
- individual tree level.

In any tree breeding programme these three levels should be exploited in that order.

Species testing phase

The use that is made of exotic species depends to a large extent on the potential of indigenous species, and in Britain our native species do not have the potential to achieve the relatively fast rates of growth that are possible in our climatic conditions. It was this possibility for increasing production that was one of the main spurs for introducing new species to Britain. In an idealised testing programme there would be several stages in the species testing phase but in the case of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Britain it was truncated to two stages: arboreta and small plots. Individuals or small groups of trees were planted in gardens and arboreta between 1840 and 1900 from seed brought back by plant collecting expeditions of Douglas, Jeffrey, Murray, Lobb and others. It was on the basis of the performance of this material, from possibly only one location and a restricted number of mother trees, that early decisions were made on the potential of Sitka spruce and its introduction on a wide scale. Only a small number of small stands were established prior to 1900, and in these Sitka spruce was mainly in mixture with other species such as Scots pine, but they indicated its potential for rapid rates of growth, high volume production and ease of establishment. We have been fortunate that the choice of this species on rather limited evidence has proved to be a success.

Seed origin testing phase

Sitka spruce has a very wide latitudinal range along the Pacific coast of North America covering some 22 degrees of latitude or almost 3000 km, but it is restricted throughout most of its range to a coastal strip only a few kilometres wide due to its dependence on adequate supplies of moisture and high humidity during the growing season (Harris, 1980). The majority of the early seed introductions for arboreta came from Washington and Oregon, as did the seed for many of the forest stands established prior to the setting up of the Forestry Commission in 1919. The main seed supplier between 1900 and 1919 was J. Rafn from Denmark, who regularly obtained seed from Grays Harbour County, Washington. The Forestry Commission made arrangements with the Canadian Government to obtain seed supplies from the Queen Charlotte Islands (Borthwick, 1924). The decision to use this particular origin was based on the similarities of latitude and climatic and ecological conditions between Britain and the Queen Charlotte Islands (Hopkinson, 1931). Seed was obtained from both Graham and Moresby Islands in the Queen Charlotte Islands group and British Columbia has continued to be the main source of supply (average of 85% of all imports 1922–1990), though some substantial quantities were imported from Washington during the period 1923–1939 (1400 kg), 1947 (1500 kg) and 1961–1971 (2300 kg).

Due to the early success with both Washington and Queen Charlotte Islands origins the Forestry Commission at first paid very little attention to seed origin variation in Sitka spruce. Early observations in nurseries showed

Table 2.1 Assessment at 38 years of the first Sitka spruce seed origin experiment, Radnor Forest

Origin	*Estimated total volume** *(m^3 ha^{-1})*	*Height* *(m)*
Siskiyou, California	712.4	26.6
Siuslaw, Oregon	685.7	28.4
Olympic, Washington	596.6	24.4
Queen Charlotte Islands, BC	566.3	22.9

*There was no record of the volume removed in the first thinning.

differences in autumn frost damage with the southern origins being more severely affected (Macdonald, 1927; Steven, 1928), but surviving plants of these origins which were planted out in the forest showed excellent growth (Lines, Mitchell and Pearce, 1971).

The first seed origin experiment was established at Radnor Forest in 1929; it only contained four seed sources, though these spanned the latitudinal range with origins from the Queen Charlotte Islands (53° 30′ N), Olympic National Forest in Washington (47° 30′ N), Siuslaw National Forest in Oregon (43° 44′ N) and the Siskiyou National Forest in California (41° 50′ N). Unfortunately the plots were not replicated. An assessment at 38 years of age gave the values presented in Table 2.1. Despite the poor initial stocking of the Oregon and Californian origins the figures indicate the greater growth potential of the southern origins.

Further series of experiments were planted between 1933 and 1959 (Lines, 1964) and they extended the sampling of the distribution of the species, mainly towards the northern end of the range. In 1960/61 a new series of experiments was established on 14 forest sites with 13 seed origins from Alaska to mid-Oregon. An analysis of 10-year height showed that on average the more southern origins were superior. In addition, when comparing individual origin values to the overall mean at each site, there is a clear indication that the southern origins show a greater response to better site conditions and that northern origins do relatively better on more testing sites but do not always out-grow more southern material (Lines, 1987). Measurement of top height and basal area at 20 years of

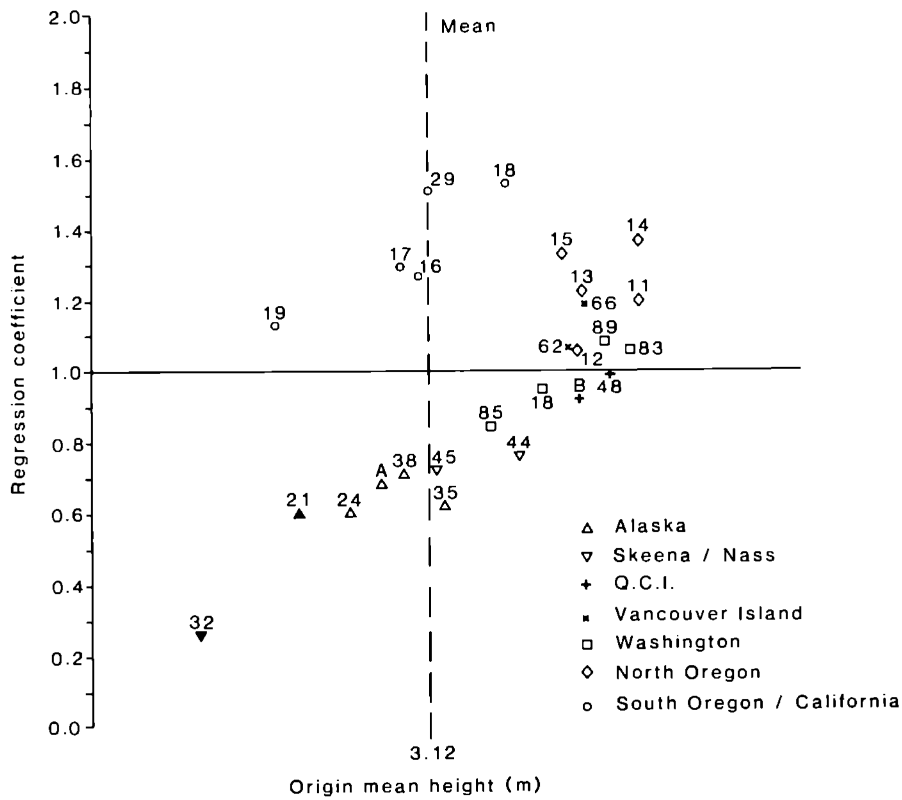

Figure 2.1 Sitka spruce IUFRO 1969/70 seed origin collections: regression analysis of 10-year height data (see Table 2.2).

age on seven of the sites gave similar results, with the Queen Charlotte Islands origin being the most stable over all sites. On the best sites, especially those in the south of Britain there was approximately a 10% difference in favour of Oregon sources over Queen Charlotte Islands material.

It was not until the IUFRO seed collections in 1969/70 that a truly comprehensive collection of material from throughout the whole distribution of the species became available (Fletcher, 1976). A total of 70 seed origins were planted on 15 forest sites (not all origins are on all sites). These origins were grouped into seven seed zones or regions and at 10 years of age these were measured for height. The results are presented in Tables 2.2 and 2.3.

Regression analysis of the data from all sites was performed using the techniques of Finlay and Wilkinson (1963). The results, shown diagrammatically in Figure 2.1, indicate that the southern origins (Oregon and California) were rather unstable but outstanding on the better sites and correspondingly poorer on the worst sites. The material from the Queen Charlotte Islands, Vancouver Island and Washington was more stable and would do well on a range of sites, while the northern material would not do well on good sites. The northern Oregon material was the fastest growing on all sites except those with early frost.

Although general zones or regions of origins can be identified there are large differences between seed sources within each zone, so it is important to identify sub-zones. Within the Queen Charlotte Islands, which cover 2° of latitude, 14 seed origins were sampled and the differences between these were as great as the differences between the regions. Within the Queen Charlotte Islands at 10 years of age the best sources were located at low elevations along the eastern part of Graham Island. The poorest one came from a high elevation on the same island.

As well as vigour it is also necessary to consider phenology, morphology and timber characteristics. As regards phenology, flushing, growth cessation and lammas growth are the most important characters.

Table 2.2 Sitka spruce IUFRO 1969/70 seed origin collections: 10-year height data (m) by seed zone or regions on 15 British sites

Seed zones or regions	*Rumster*	*Craigellachie*	*Achaglachgach*	*Blairadam*	*Benmore*	*Glentress*	*Castle O'er*	*Arecleoch*	*Wark*	*Thornthwaite*	*Dalby*	*Mathrafal*	*Ystwyth*	*Rhondda*	*Wilsey Down*	*Mean*
Alaskan	2.96	2.34	3.40	3.21	3.39	2.15	2.22	2.76	2.31	3.23	2.96	2.65	2.50	2.39	3.76	2.80
Skeena/ Nass	2.82	2.33	3.23	3.34	3.40	2.06	2.44	2.57	2.64	3.03	3.24	2.90	2.54	2.41	3.71	2.82
QCI	3.48	2.68	4.12	4.02	4.10	2.24	2.44	3.33	3.03	4.08	3.73	3.57	2.95	3.28	4.84	3.42
Vancouver Island	2.89	2.92	4.52	3.74	3.97	2.22	2.12	2.76	2.97	4.43	3.84	3.56	2.95	3.47	5.02	3.37
Washington	2.93	2.47	4.39	3.94	3.96	2.24	2.46	3.26	3.01	3.91	3.63	3.86	2.89	3.18	4.58	3.34
North Oregon	3.17	2.56	4.88	3.71	4.04	2.28	2.26	3.31	2.64	4.20	3.84	3.91	3.05	3.28	5.33	3.44
South Oregon/ California	2.78	3.29	4.74	2.54	3.10	1.69	1.44	2.57	1.84	3.42	3.49	3.56	2.63	3.15	5.41	2.89
Overall mean	2.98	2.48	4.22	3.41	3.65	2.10	2.15	2.93	2.54	3.69	3.49	3.42	2.76	2.98	4.68	3.12
Elevation (m)	30	290	152	290	20	440	280	140	190	487	183	350	510	440	285	

Flushing in Sitka spruce has been shown to be controlled by temperature in the form of a combination of the number of day degrees above 5°C after 1 February and the amount of winter chilling experienced by dormant buds (Cannell and Smith, 1983). Extensive measurements of flushing have been made on all the main series of seed origin experiments both in the nursery and in the field and these have shown that there is greater variation between individual trees within a seed origin than between the mean values of different origins (Lines and Mitchell, 1966; Kraus and Lines, 1976; Burley, 1966). Northern origins tend to take longer to pass from the bud swelling stage to the fully flushed stage. The Oregon and California origins tend to be slightly later flushing, but there is no meaningful correlation between latitude of the seed origin and flushing date.

Growth cessation is a more important characteristic as it affects both susceptibility to low temperatures and total shoot growth. In the first year especially, Sitka spruce has the capacity to continue growth well into the autumn and the date of growth cessation is very much dependent on photoperiod. In subsequent years in the nursery similar growth patterns are observed, with northern origins stopping growth first as photoperiod is reduced (Pollard, Teich and Logan, 1976), and there is a strong correlation between length of growing season or progress of budsetting and latitude of seed origin (Kraus and Lines, 1976; Kleinschmit and Sauer, 1976; Kranenborg and Kriek, 1980). Measurement of growth cessation in the field is difficult so only limited reliable data are available, but they suggest that differences in the length of growing season between origins continues for a number of years (Cahalan, 1981).

Flushing and growth cessation are important in the context of damage by spring and autumn frosts. The small differences in flushing times between origins means that there is little scope for selecting material at the origin level to avoid spring frost damage. There is, however, scope to select origins whose patterns of growth cessation and autumn hardening are best suited to British conditions. Southern origins are more severely damaged than those from the Queen Charlotte Islands and Alaska and therefore the latter should be used where there is the possibility of temperatures dropping to −5°C and below in September.

No major morphological differences have been found between seed origins of Sitka spruce so it is not possible to identify unknown seed origins on a morphological basis. Biochemical techniques have been used with limited success on Sitka spruce (von Rudloff, 1977; Forrest, 1980; Yeh and El-Kassaby, 1980) but they can be used to identify hybrids with *Picea glauca* (Hanover and Wilkinson, 1970; Yeh and Arnott, 1985) which are also morphologically distinct.

The majority of wood property studies have been based on material from Queen Charlotte Islands seed origins. Samples were tested from the four seed origins in the Radnor experiment for wood density measurements but the results were affected by the variable stocking in the plots. The Queen Charlotte Islands origin had the highest density and Oregon the lowest. A wider range of origins from the 1960/61 series of experiments was sampled at 9 years of age and again the northern origins had the highest wood density, due partly to their slower rates of growth. There was an inverse correlation between wood density and stem volume (Broughton, 1962; Brazier, 1972), a relationship which has also been found in a recent study in Ireland (Murphy and Pfeifer, 1990).

A study was recently initiated to determine whether there were differences in the strength properties of wood between Queen Charlotte Islands and Washington origins. Logs were taken from a Queen Charlotte Islands origin and six Washington origins in an experiment planted at Gwydyr Forest in 1950. Preliminary results from a stress grading exercise on sawn batons indicate that there are no significant differences between the origins. Measurements of specific gravity, percentage late-wood and tracheid length also showed no significant differences between the origins, although there was large within origin variation in these characters. It is possible therefore to select for individuals with high volume production but without a corresponding decrease in density. Considerable gains in growth rate (volume) can be achieved at the expense of a slight decrease in wood density.

The seed origin testing phase has indicated that there are differences between seed origins in growth rates, phenology and wood properties and that by selecting the correct seed origin gains can be achieved. The Queen Charlotte Islands origins are good general purpose sources which are reasonably frost hardy, resistant to exposure and produce acceptable timber. On less exposed, more favourable sites, especially in south-west England, Wales and parts of west Scotland, origins from Washington and on some sites Oregon can be used with increases in timber production but with the possibility of a slight decrease in strength properties. These origins have an increased risk of autumn or winter frost damage and may require protection during the nursery phase. Northern origins from Alaska do not appear to have any place in British forestry except on very frosty sites and even then Sitka spruce may be the wrong species choice. All the seed origin experiments have shown that there is large within origin variation in the characteristics measured, indicating the potential for further improvement through breeding.

Individual testing or breeding phase

The seed origin testing phase has identified the most suitable origins for British conditions but there is scope for further improvement by selecting good quality stands and superior individuals within these origins. The partitioning of the genetic variation between and within origins tends to vary by species and individual trait but on average for vigour characteristics 40% is accounted for by between origins and 60% by within origins.

Although substantial gains can be made in the breeding phase with a species like Sitka spruce there is the disadvantage of a long breeding cycle due partly to irregular flowering and the interval between flowering years. Breeding strategies have to be devised to overcome where possible these disadvantages and reduce the time lag before improved stock is utilised in commercial forestry.

Seed stands

Immediate improvement can be obtained by selecting the best stands within the selected origin and collecting seed from them when there are heavy cone crops. These stands are selected on a phenotypic basis and have to satisfy the

Table 2.3 Sitka spruce IUFRO 1969/70 seed origin collections: 10-year height data expressed as a percentage of the mean at each site

Region		IUFRO Number	Seed origin	Rumster	Craigellachie	Achaglachgach	Blairadam	Benmore	Glentress
Alaska		3021	Yakutat	105	89	75	82	83	90
		3022	Dyea, Skagway Area	91	92	–	85	87	95
	I	3024	Duck Creek, Juneau Area	102	100	80	91	90	98
		3025	Ohmer Creek, Mitkof Is	113	–	88	102	100	96
		3027	Craig, Prince of Wales Is	98	81	76	96	96	100
	II	69(7986)	Craig, Prince of Wales Is	–	–	–	–	–	–
		3028	Old Hollis, Prince of Wales Is	104	93	–	–	103	90
		3030	Ward Lake, Tongass	108	86	84	96	96	95
		3035	Moss Point, Annette Is	98	106	85	102	101	112
		66(7985)3	Seward, Kanai Peninsula	86	82	74	73	70	–
	I	69(7986)3	Hoonah, Chicagof Is	84	100	–	86	87	–
Skeena/Nass Rivers		3026	Derrick Lake, Nass River	90	99	73	94	87	80
	III	3032	Kitwanga, Hazelton Area	89	88	58	–	–	89
		3033	Zolap Creek, Nass River	95	99	76	91	86	97
		3038	Pacific, Skeena River	80	101	82	101	95	96
	IV	3039	Kitsumkalum Lake, Terrace	94	–	–	94	–	101
		3041	Shames, Skeena River	94	91	79	80	77	87
		3042	Kaslks River, Skeena River	85	82	82	88	80	90
		3043	Hays Mtn, Prince Rupert	79	–	72	77	–	–
	V	3044	Inverness, Prince Rupert	101	101	95	108	102	100
		3045	Aberdeen Creek, Skeena River	94	98	88	102	94	96
		3046	Wedene River, Kitimat	90	97	92	100	80	101
		3047	Humpback Creek, Porcher Is	90	89	95	79	93	110
Queen Charlotte Islands		3048	Masset Sound, Graham Is	122	109	103	116	117	102
		3049	Link Road, Juskatla, Graham Is	112	89	93	110	107	101
		3050	Copper Creek, Moresby Is	105	103	101	98	104	112
		3051	Moresby Camp, Moresby Is	113	101	93	113	104	104
		3052	Tasu Creek, Moresby Is	91	90	98	102	99	103
		3053	Jedway, Moresby Is	113	103	104	112	105	101
	VI	3068	Naden Harbour	111	111	110	107	111	108
		3069	Ain River, Masset	119	113	109	111	108	106
		3070	Dinan Bay, Masset	90	105	105	111	102	108
		3071	Tlell, Graham Is	110	103	–	113	115	–
		70(7111)500	Towhill, Masset	115	–	112	110	109	110
		70(7111)501	Queen Charlotte City	112	107	105	–	109	96
		70(7111)502	Maud Is, Skidegate	117	107	113	107	118	108
		70(7111)Lot 2	Masset (Commercial Seedlot)	112	112	102	113	105	104

98	84	87	78	80	–	–	–	–
87	56	90	68	76	64	74	74	53
85	71	90	86	86	–	–	–	–
79	96	92	85	80	–	–	–	–
95	97	97	103	95	–	–	–	–
93	84	86	78	–	–	–	–	–
80	84	81	80	81	–	–	–	–
89	80	76	77	82	–	–	–	–
130	112	104	96	112	99	102	87	96
99	90	114	87	102	93	102	85	91
94	89	88	87	97	–	–	–	–
107	105	80	88	91	–	–	–	–
107	110	118	110	118	106	109	109	106
96	93	108	98	96	–	–	–	–
121	110	98	99	103	–	–	–	–
110	97	108	105	93	–	–	–	–
109	112	104	96	106	–	–	–	–
109	108	108	111	103	–	–	–	–
110	97	112	107	106	–	–	–	–
121	112	116	105	111	–	–	–	–
115	104	100	102	100	–	–	–	–
–	117	131	–	112	–	–	–	–
116	107	128	113	102	–	–	–	–
108	117	102	111	113	–	–	–	–
109	97	112	110	108	–	–	–	–
–	113	116	115	106	104	105	113	102

Table 2.3 *continued*

Region				Rumster	Craigellachie	Achaglachgach	Blairadam	Benmore	Glentress
Vancouver Island	IX	3056/3057	Holberg	102	108	102	–	102	108
	X	3058	Salmon Bay	103	105	104	–	104	102
		3059	Fair Harbour	124	104	112	117	107	108
	IX	3061	Tahsis Inlet, Nootka Is	101	99	102	121	108	108
	X	3062	Big Qualicum River	85	128	108	–	109	105
	IX	3065	Port Renfrew	114	94	107	103	103	104
	X	3066	Muir Creek, Nr Sooke	–	–	116	–	–	99
	IX	68(7116)6	Tofino	99	103	–	104	109	107
Washington		3001	Bellingham	95	85	108	112	107	100
	XI	3002	Port Angeles	96	116	110	105	96	107
		3067	Stillaguamish R., Puget Sound	97	111	96	109	97	100
	XII	3003	Forks, Olympic Rain Forest	107	102	116	116	115	106
		3004	Kalaloch, Olympic Rain Forest	109	114	118	116	124	108
		3005	Brinnon, Puget Sound	103	94	97	101	95	102
	XI	3006	Shelton, Puget Sound	97	97	103	105	109	100
		3007	Humptulips, Olympic Rain Forest	101	102	108	110	115	106
	XII	3008	Hoquiam, Grays Harbour	114	116	113	104	123	105
		3009	Raymond, Willapa Bay	94	110	118	127	105	109
		3010	Naselle, Willapa Bay	92	101	103	106	112	96
North Oregon		3011	Astoria	97	113	119	109	112	104
	XIII	3012	Necanicum	103	103	112	114	104	108
		3013	Tillamook	–	104	121	108	116	105
		3014	Newport	118	109	124	107	114	107
	XIV	3015	Florence	–	99	129	91	99	101
S. Oregon & California		3016	Denmark, Oregon	98	103	118	79	76	94
	XV	3017	Gold Beach, Oregon	–	110	126	69	74	82
		3018	Brookings, Oregon	96	109	124	96	89	86
		3019	Big Lagoon, California	85	77	–	58	86	–
	XVI	3020	Crescent City, California	–	93	129	58	94	64
			Experiment mean height (m)	2.97	2.45	4.02	3.50	3.68	2.15

Castle O'er	Arecleoch	Wark	Thornthwaite	Dalby	Mathrafal	Ystwyth	Rhondda	Wilsey Down
97	111	110	104	109	–	–	–	–
118	101	108	107	109	–	–	–	–
116	120	119	116	103	–	–	–	–
119	116	113	109	–	–	–	–	–
90	95	115	119	118	105	105	115	104
112	110	108	112	96	–	–	–	–
93	89	115	125	–	104	109	120	112
121	102	101	101	108	–	–	–	–
101	116	94	94	106	–	–	–	–
105	108	94	108	87	–	–	–	–
104	99	114	99	–	–	–	–	–
107	115	127	115	122	120	108	112	96
134	127	109	103	114	–	–	–	–
101	104	118	98	117	104	92	105	100
116	107	90	106	87	–	–	–	–
134	119	121	101	123	–	–	–	–
96	116	117	105	117	–	–	–	–
103	124	103	115	111	118	110	103	97
112	94	119	103	107	112	110	110	102
112	127	102	124	132	114	109	114	111
103	103	115	103	117	112	108	105	111
91	117	91	112	100	117	110	115	107
95	114	97	129	120	116	115	105	122
87	93	107	112	106	116	114	116	123
53	87	77	90	98	111	99	119	115
58	82	73	87	103	96	104	113	116
50	103	83	97	130	108	104	107	131
–	81	56	–	79	97	75	98	103
–	76	68	110	112	111	94	97	117
2.31	3.00	2.58	3.60	3.35	3.40	2.75	2.96	4.64

Forest Reproductive Material Regulations (1977) in order to be registered and the seed marketed under the 'Selected Category'. The stands have to be isolated from contaminate pollen from neighbouring undesirable sources and the individual seed trees have to be above average for the species in size, stem quality, branching habit and health. The offspring from these selected stands, which will have been subjected to a degree of natural selection when grown under British conditions, will give an improvement over unselected material imported from the Pacific North-west. The genetic gain achieved by using planting stock from the best stands of the best adapted origin will be small (in the region of 1 or 2%), but it can be achieved at a minimal financial cost. Seed stands should be considered as the preliminary stage in obtaining genetically improved seed and will be phased out as material of higher genetic quality becomes available (e.g. from seed orchards).

Statement of genetic principles

Vigour, form, wood properties or any other characteristic which is subjected to selection can be referred to as a *trait*. A tree as observed at the time of selection for a particular trait is its *phenotype*. This is an expression of the tree's genetic quality, its *genotype*, and the environment in which it is growing. In addition to the environmental effect at a single site, there may be differential expression of the genotype itself across a range of sites and this *genotype* x *environment interaction* may also affect the phenotype. Phenotype may thus be a poor indicator of genotype.

Genotype may be evaluated by study of the *genetic variation* of a trait. The total genetic variation can be partitioned into two. The variation which is passed on to offspring in the next generation is the *additive* portion. The remaining part, which is not inherited in so straightforward a manner, is the *non-additive* portion.

Where there is no control over the identity of the male parent of a cross, or if a number of different individuals are used as the male parent in an artificial pollination, a *half-sib* family is produced. Additive variation can be evaluated by comparing half-sib families of selected trees in progeny tests. *Half-sib progeny tests* can be used to estimate firstly the level of additive genetic variation as a proportion of the total phenotypic variation, the *narrow sense heritability* of the trait, and secondly the contribution of each individual to this additive variation, its *breeding value* or *general combining ability*. Because of the possibility of genotype x environment interaction, progeny testing must be carried out over a range of sites and an overall or average heritability estimate obtained. Heritability estimates may also vary with age.

Heritability can take values between 0 and 1, a higher value reflecting a greater level of additive genetic control. Breeding values must be weighted by narrow sense heritability estimate to calculate *genetic gain*. This gain would apply to all systems of improvement in which the end product was half-sib progeny material such as a *seed orchard* or *bulked half-sib family mixtures*.

Where specific crosses between two parent trees are made, *full-sib* families are produced. Non-additive variation may appear in *full-sib progeny-test* as a departure from expected family performance based on breeding values of the parents. A full-sib family showing non-additive variation reflects the *specific combining ability* of the parents.

Where total genetic variation is evaluated, *broad-sense heritability* can be estimated. This can be derived from systems of testing in which the additive and non-additive effects cannot be separated, such as a clonal test comparing vegetatively propagated material from selected trees. Broad sense heritability is used in the calculation of genetic gain in systems of improvement which exploit both additive and non-additive variation such as *improved clones* in species such as poplar or *bulked full-sib family mixtures*.

The Sitka spruce breeding programme is based on improvement by sexual means and therefore narrow sense heritability is more important. The main aim is to improve general combining abilities and thus use only the additive part of the genetic variance.

Individual tree testing

The breeding phase of the improvement programme involves the selection of potential breeding trees or superior individuals ('plus trees'), evaluating their genetic quality and then utilising those with the greatest potential to produce seed or vegetative material for use in commercial forestry.

A total of 2800 outstanding phenotypes of Sitka spruce have been selected in the best stands of the species covering a wide range of site types. The early selections, prior to 1973, were made using a very intensive selection procedure in which selection was in the order of 1 : 75 000. Early results from progeny tests indicated that heritability values for vigour characteristics were relatively low compared to those for form characters, and that the former could only be reliably estimated by means of a genetic test. Latterly less emphasis has been placed during the phenotypic selection process on vigour and more on straightness and branching. The selection intensity for vigour has therefore been slightly reduced but that for form increased. The majority of the trees (2000) were selected in stands of Queen Charlotte Islands origin and those which prove the most outstanding in progeny trials will form the basis of the general breeding population. The remaining selections were made within stands that might provide individuals for the Southern Breeding Population (Washington/Oregon) and the Northern Breeding Population (material believed to be more frost hardy and from drier sites).

The evaluation of the genetic quality of the selected 'plus trees' is undertaken in progeny tests which are relatively long term, lasting 15 to 20 years. Seed which is collected from the 'plus tree' for evaluation is produced either by wind pollination (where there will be a range of unknown fathers) or by poly-crossing (controlled pollination involving a mixture of at least 10 known fathers). The seed of individual trees is sown in a greenhouse and then the resulting seedling families are 'pricked out' into nursery beds at uniform spacing in replicated plots. Standard commercial seed lots are included in all tests as reference material. The families are planted out on a range of sites in Britain when 2 years old; a minimum of three representative test sites are used. Each family is represented by a minimum of 120 plants and they are assessed at periodic intervals for survival, height, diameter and form (straightness and branching).

There are very good correlations between measurements made at age 6 to 8 and 20 to 30 years of age (Gill, 1987; Lee, 1990) so preliminary selections of families for inclusion in the breeding population can be made at between 6 and 8 years of age. Parents which produce families that on average are 15% greater in height than the Queen Charlotte Islands control and 7% taller than the overall family mean are included in the breeding population.

In addition to vigour and form characters, assessments are also made of wood quality based on measurements made with a 'pilodyn', which gives a non-destructive estimate of wood density by forcing a pin into the tree. The strength of the timber is inversely related to the penetration of the pin. This assessment cannot at present be done until the progenies are 15 to 20 years of age; thus final confirmation of a parent tree's inclusion in the breeding population must be delayed until the wood quality has been assessed. Currently the standards of selection used in Britain are very high, with only 10% of the original 'plus tree' selections entering the breeding populations. The aim is to have 200, 100 and 100 tested trees in the General, Southern and Northern breeding populations respectively.

Those parent trees which are shown to be good progeny producers are propagated by grafting and established in breeding clone banks. These banks not only preserve this important genetic material but also provide, in a single location, a source of pollen and female flowers to create new genetic combinations.

Seed orchards

Seed orchards are the means by which the end product of the breeding programme is produced for commercial use. They consist, so far as Sitka spruce is concerned, of the 40 parents identified as best in progeny tests, each represented by 40 to 50 genetically identical (clonal) propagules of each parent created by grafting. Grafts are planted in intimate mixture to produce the maximum of inter-crossing between parents. The clonal seed orchards are managed for seed production and not timber, so they are located in areas of the country that are favourable to the production of male and female flowers and on sites which are free from pollen contamination. In the case of Sitka spruce no seed orchards are set up with untested clones, so there is a delay of at least 20 years between the selection of a 'plus tree' and grafts of that same tree being planted in a seed orchard.

Sitka spruce grown from seed does not normally flower until it is 25 to 30 years old and grafts from the parent trees, which can be considered 'mature', do not naturally flower heavily in the seed orchards until 8 to 10 years after grafting. Research over the past 10 years has shown that Sitka spruce grafts can be stimulated into flower production by chemical and cultural techniques (Philipson, 1987). Trials are now proceeding to evaluate the feasibility of establishing seed orchards in polythene 'flowering' halls to produce seed on young containerised grafts and at regular intervals. If successful this system would shorten the time taken to reach the stage of commercial production of genetically improved seed (Philipson and Fletcher, 1990).

Vegetatively propagated families

In any breeding programme it is important that the genetic gain per unit of time is maximised. There is therefore a need to reduce the length of the breeding cycle: selection of individuals, progeny testing, grafting, seed orchard establishment through to seed harvesting and finally planting of genetically improved material in commercial forests. The length of this cycle for Sitka spruce is normally between 25 and 30 years.

Vegetative propagation can be used to shorten that part of the cycle between the identification of superior families and the planting of genetically improved stock. Sitka spruce has shown itself to be amenable to bulk vegetative propagation by cuttings if young material can be used (Mason, 1984; John and Mason, 1987). Controlled pollinations can be carried out in seed orchards or clone banks between 15 to 20 identified superior female trees (clones) and a mixture of pollens (polymix) from 10 to 15 of the best available males. This simulates to some extent what happens in a seed orchard except that the pollination is limited to the best male and female clones. Only limited quantities of seed can be produced by such means, but with bulking-up factors of 500 rooted cuttings per seed (John and Mason, 1987) this can generate large quantities of genetically improved planting stock. This method of production reduces the breeding cycle from about 25 years to around 18 years.

Trees which are produced by this method cost between two and three times as much as normal bare root stock (Mason, 1992), but this can be justified because the increased revenue from realising the *potential* genetic gain earlier (Mason and Harper, 1987; Lee, 1992) exceeds the extra cost of the planting stock. As the progeny testing programme progresses new superior genotypes will be identified and can immediately be added to the list of clones used for producing 'bulked family mixtures', thus increasing the potential genetic gain. The potential genetic gain currently available from the mass vegetative propagation of these 'bulked family mixtures' and from approved clonal seed orchards is 15% in height at 10 years, which will probably translate into an increase of 15% in volume at rotation age (Lee, 1990; 1992).

Future developments

The potential gains from Sitka spruce breeding will increase as new clones enter the production population, but as clonal seed orchards and 'bulked family mixtures' only exploit additive genetic variance the increases will be limited. In order to obtain further gains it will be necessary to utilise the non-additive portion of gene-tic variance, which can only be captured by using specific crosses.

The approximately 200 clones selected to enter the General Breeding Population will be divided into groups (sub-lines) and hundreds of random specific crosses will be made within the

Plate 1. *Selection of plus trees based on vigour, form and health.*

Plate 2. *Isolation of female strobili and pollination with a mixture of pollen from ten 'superior' trees.*

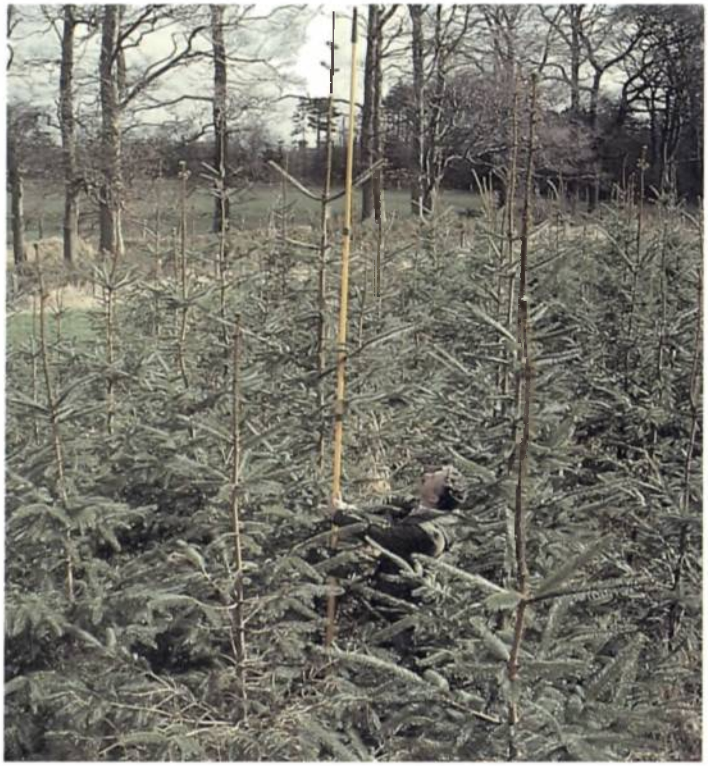

Plate 3. *7-year height assessment of a fast growing clone in a replicated clonal test established at Bush Estate, near Edinburgh.*

Plate 4. *One-year-old stock plants raised in a polythene house.*

Plate 5. *Hedges for production of cutting material.*

Plate 6. *Lifting cuttings in July that were inserted the previous March.*

Plate 7. *Growth of a block of 6-year-old cuttings in the Laigh of Moray.*

Plate 8. *Participants in the Super Sitka meeting inspecting a tree improvement trial.*

sub-lines. Each clone will be used in 5 or 6 artificial crosses in which both the parents are known. Trials of the resulting progenies should indicate a number of families whose performance is superior to predictions of their growth based on the general combining abilities of their two parents.

A programme for the production and testing of specific crosses has been started but it will be another 8 to 10 years before we have the first preliminary results. Once the families where the parental genotypes combine to provide outstanding progeny have been identified they will be recreated by controlled pollination and the resulting small amounts of seed multiplied up by vegetative propagation. It is not known for certain what the potential genetic gain from such material will be, but it is predicted that for the first series of full-sib families it should be in the region of 25 to 30% for 10-year height relative to unimproved material from the Queen Charlotte Islands.

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Paper 3

Reducing the cost of Sitka spruce cuttings

*W. L. **Mason**, Silviculture (North) Branch, Forestry Commission, Northern Research Station, Roslin, Midlothian EH25 9SY, UK.*

Abstract

Over one million genetically improved Sitka spruce cuttings were planted in Great Britain in 1990. However, these plants cost two to three times more than unimproved seedling stock which has reduced demand. Analysis shows that labour input in the production of second cycle cuttings is a major reason for these high costs. A number of alternative techniques can be used to reduce costs and improve rooting of Sitka spruce cuttings. These include propagation in seedling containers to eliminate transplanting, screening of cuttings before insertion to maximise rooting, stock plant management maintaining adequate nitrogen levels, freezer storage to allow two crops to be produced per year and insertion in covered nursery beds to reduce capital costs. Preliminary analysis indicate that use of some or all these techniques could help reduce production costs so that current prices could be reduced by up to one-third.

Introduction

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is the most important coniferous species used in British forestry comprising over 50% of current planting. An intensive breeding programme has been carried out with this species for more than 30 years with the aim of improving vigour, form and timber quality of the tree crop (Faulkner, 1987). The superior genotypes which have been identified offer appreciable genetic gains over unimproved material (Gill, 1983). The original plan was to realise these gains by establishing random-mating seed orchards and to harvest the seed for use in conventional nursery production. Unfortunately, this approach ran into difficulties due to the shy flowering nature of the species, problems in obtaining matched flowering on a seasonal basis, and the time necessary to establish a large area of seed orchard of improved families which had been progeny tested. The development of successful propagation techniques in spruce species using stem cuttings (Kleinschmit and Schmidt, 1977; John and Mason, 1987) provided a feasible commercial alternative to the original plan.

A number of British forest nurseries began commercial production of stem cuttings of genetically improved Sitka spruce in the mid-1980s. By the turn of the decade, their combined production was well in excess of 1 million forest use cuttings per year and was expected to near 5 million cuttings per year by the mid-1990s (Mason, 1991). However, Sitka spruce cuttings are more costly to produce than unimproved seedling planting stock (there is no improved seedling stock available as yet) and a difference in price of two to three times per plant (1989/90 figures) has reduced demand. This reduced demand has occurred despite financial appraisals which indicated that the level of genetic gain justified this higher price (Mason and Harper, 1987). Recent changes in Government support for private forestry have also had an influence, since a private forest investor can no longer offset the higher cost of improved planting stock against income tax. Instead there is a flat-rate planting grant irrespective of the cost of plants and their genetic quality.

It is clear that the retail price of cuttings relative to seedling planting stock has a major influence on the demand for improved material. It is arguable that relative price is more important than the level of genetic gain since the latter is

Table 3.1 The standard system for producing Sitka spruce cuttings: stages, commercial success rate[1] and contribution to costs[2]

Year	*Stage*	*Operation*	*Success rate (%)*	*Cost contribution[3] (%)*
1	Stock plant	Sow seed	80	3
2	Stock plant	Grow on	99+	
3	First propagation cycle	Rooting	90	
4	First propagation cycle	Rooted cuttings grown on in transplant lines	90	11
5	Second propagation cycle	Rooting	85	
6	Second propagation cycle	Rooted cuttings grown on in lines: culled before dispatch to forest	80	79

Notes:
1. After Blackwood (1989).
2. After Mason (in press); costs were calculated net of overheads and a total cost (no overheads) of *c.* £130 per 1000 forest use plants is assumed.
3. An additional 7% is contributed by miscellaneous nursery expenses.
4. Multiplication rates per cycle are 65-70 first cycle cuttings per stock plant and *c.* 10 second cycle cuttings per first cycle plant (Blackwood, 1989) without allowing for losses.

realised some decades hence in an uncertain future whereas the former is paid now, usually under budget constraints.

This paper will briefly outline current propagation techniques, consider some alternative approaches suggested by recent experiments, and discuss how these alternatives might affect production costs.

Current propagation techniques

Propagation techniques used in Britain generally follow those described by Mason (1984). The system is outlined in Table 3.1 with more details given in the Appendix. There is normally a six-year gap between the sowing of seed and the dispatch of cuttings for forest planting. This interval comprises a two-year stock plant phase followed by two propagation cycles of two years each. Stock plants are normally raised in 3-4 litre containers in unheated polyhouses. Cuttings (normally 8 cm in length) are collected in spring (March) and inserted with minimum delay with no rooting hormone applied. Both tip and base cuttings are used to increase bulking-up factors, particularly in the first cycle. Cuttings are generally rooted in trays under intermittent mist in an open substrate with an air-filled porosity (AFP) >15% (Mason and Keenleyside, 1988). After rooting, cuttings are lined-out (bare-root) in a nursery in late summer (August) to be grown on for a further 18 months. Second cycle cuttings are then collected using the same timing and technique as first cycle ones. First and second-cycle cuttings are given different nutritional regimes, different spacing in the lines, and only second cycle cuttings are undercut. The multiplication factors being achieved in commercial practice over two cycles are around 400 plantable cuttings per stock plant (Blackwood, 1989).

Table 3.1 indicates that the second propagation cycle is responsible for the majority of production costs. Labour is the major element of these costs since collection, insertion and lifting of cuttings are all currently labour-intensive operations with limited possibility of mechanisation at present. Possible ways of reducing costs include eliminating labour-intensive operations by inserting cuttings in containers to avoid lining-out, the screening of cutting quality before insertion to improve rooting, the rooting of cuttings in covered nursery beds to reduce the requirement for expensive misthouses, and the use of freezer storage to allow two crops to be propagated in one growing season. The next section considers the experimental evidence for these approaches.

Experiments on alternative approaches

Experiment 1. Propagation in containers and trays

An early experiment examined the feasibility of rooting cuttings in containers used for growing seedlings in comparison with standard propagation trays. The containers used were 'Multipots' (GPG Containers Ltd., Dunstable, UK) either 67 or 90 cc in volume, 9 or 12 mm deep respectively with 67 cuttings per container set. Standard propagation trays were 380 × 230 × 60 mm deep (internal dimensions) with drainage holes in the base and 45 cuttings per tray at 4 cm spacing.

The effect of different propagation substrates was also considered. Cuttings were rooted either in pure sphagnum moss peat (SMP) or in two-way mixtures between SMP and either grit (lime-free; 2-3 mm average diameter), vermiculite or perlite. The mixtures were varied in the proportion 3:1, 1:1, and 1:3 by volume.

Tip cuttings (8 cm long) were collected from 3-year-old nursery transplants of Queen Charlotte Islands origin on 14 February 1983. They were cold-stored (+2°C) in sealed polythene bags until insertion on 28 February 1983. Cuttings were then kept in the Newton nursery misthouse (Mason and Keenleyside, 1988) until assessment of rooting percentage and root score on 28 July 1983. The latter is a measure of increasing root volume scored 1-10 using photographic standards; root score 1 is about 5 mg root dry weight, 5 about 60 mg and 10 around 275 mg. A randomised block design was used with three container/tray types and 12 substrates (pure SMP was repeated three times) replicated two times to give 72 plots. Results were analysed by analysis of variance with rooting percentages transformed by arcsin.

Experiment 2. Propagation and nutrition in containers

This study compared the effect of different levels of nutrition upon the rooting and subsequent growth of cuttings propagated in a standard seedling container. Previous trials (Experiment 1) had shown cuttings could be rooted in containers, but growth was poor with few plants exceeding the lower height limit of 15 cm for forest usability with bare-root stock (Aldhous, 1989) at the end of the first season.

Tip cuttings 8 cm length were collected from 2-year-old stock plants of an improved bulk family mixture (84(MØØ13)) on 23 March 1989. Cuttings were inserted on the same day into a substrate of sphagnum moss peat; composted pine bark; perlite (1:1:1 by volume) in 'Sherwood' Rootrainers[1] (Ronash Ltd., Kelso, UK; volume of 175 cc).

Both basal and liquid (top-dressing) fertiliser regimes were contrasted. The basal fertilisers were: control – no basal fertiliser; Osmocote 'Miniprill' (Sierra UK Ltd., NPK 18-6-10; 3 to 4 months release) incorporated at 1.5 kg product m^{-3} of compost; 'Gold N' (sulphur coated urea; NPK 35-0-0) at 1.5 kg product m^{-3} of compost plus trace element frit (No. 253A) at 0.3 kg product m^{-3}. The last treatment had increased height growth of Sitka spruce cuttings in previous trials (Mason, 1989). Four liquid fertiliser regimes were compared; control – no liquid fertiliser; a high nitrogen feed (NPK; 2-1-1) applied twice weekly from the start of weaning (11 July 1989) at 200 ppm N with 4 litres solution m^{-2} of compost; a high potassium feed (NPK; 2-1-4) applied at 100 ppm N at the same time and rates as the high N treatment, and a balanced feed (NPK; 1-1-1) applied at 200 ppm N at equivalent rates and times. The experiment also included a comparison of different conditioning regimes (drought stressing, photoperiod reduc-

[1] *Commercial names are for information only and do not represent an endorsement by the Forestry Commission.*

tion), but these had minimal effect upon treatments and are not considered further.

A split-plot design was used with the four liquid fertiliser regimes replicated 13 times to give 42 main plots. Each main plot was randomly split into three basal fertiliser subplots. Each subplot consisted of 32 tip cuttings, each in one Rootrainer cell. Four randomly selected blocks were destructively assessed at 20 weeks after insertion for height, rooting percentage and root score. The remaining blocks were assessed for height and survival at 30 weeks. Results were analysed in the same way as Experiment 1.

Experiment 3. Management of stock plants

Stock plants are frequently grown in greenhouses where favourable growing conditions produce tall plants (often >1 m in 2 years) and the maximum yield of first cycle cuttings. However, plants grown in such conditions require careful watering and fertilisation to ensure that good quality cuttings are produced. This can be particularly important if stock plants are grown in containers (i.e. <4 litres) where they may become potbound in the second growing season.

In April 1986, 1-year-old stock plants of a bulked family mixture (84(MØØ13)) were repotted into black polythene containers of either 1, 2, 4 or 8 litre capacity. The potting substrate was three parts sphagnum moss peat to one part lime-free grit by volume. Basal fertiliser regime followed recommendations for container-grown stock being given supplementary feeding (Anon., 1985; p. 46) containing potassium nitrate (13% N; 38% K) at 0.75 kg m^{-3}, single superphosphate (8.7% P) at 1.5 kg m^{-3}, ground limestone at 1.2 kg m^{-3}, magnesium limestone (11-13% Mg) at 2.4 kg m^{-3} and fritted trace elements at 0.3 kg m^{-3}. Initially all treatments were fertilised once weekly with a balanced feed giving 200 ppm NPK (B regime). In July, August and September half the plants were given a weekly high nitrogen feed (HN) with 270 ppm N and 135 ppm PK with the remainder kept on the B regime. A randomised block design was used with eight treatments (four pot sizes by two fertilisers) replicated six times with one stock plant per plot. Heights of plants were assessed at the beginning and end of the growing season. Bulked samples from each treatment were collected in April, July, August, September and November for foliage analysis. Total N was determined by the indo-phenol method, P by the phosphomolybdenum method and K by a plasma spectrometer determinator, after a Kjeldahl digestion of the plant material.

In March 1987 tip cuttings were collected from all stock plant treatments and inserted in a 4:1 lime-free grit:sphagnum moss peat substrate. A randomised block design was used with five replicates and a plot size of 45 cuttings at 4 cm spacing in a seed tray. Treatments were assessed for percent of cuttings rooted and root score after 22 weeks in the mist propagation unit. Propagation regimes were the standard ones used in the Newton nursery mist house except that no liquid fertiliser was applied after the cuttings had rooted. Data were analysed in the same way as in Experiment 1.

Experiment 4. Storage of cuttings for summer insertion

A problem with current propagation techniques is that cuttings have to be collected and inserted over a relatively short period in the spring. If cuttings could be stored after collection and then be inserted later in the year after the first crop had been lifted, it would be feasible to produce two crops in one year. This would spread the workload as well as reducing the number of mist propagation houses required for a given programme.

To test this possibility, 8 cm tip cuttings were collected from 3-year-old nursery plants of Queen Charlotte Islands origin on 21 January, 11 February and 15 March 1988. These dates were chosen to cover different periods in the dormancy cycle of Sitka spruce as dehardening occurs after peak cold-hardiness in mid-winter. All cuttings were cold-stored in sealed polythene bags immediately after collection at temperatures of either +1°C (cold storage) or −1°C (freezer storage). Prior to storage in bags the cuttings were either blotted dry to remove surplus water or were placed directly in the bags. This treatment was incorporated because a previous experiment (Mason, 1988) had suggested that cuttings with surface moisture on their foliage could be damaged during storage. All treatments were removed from storage and were inserted on 13 July 1988 after 25, 21 and 16 weeks storage respectively. A randomised block design was used with 12 treatments (three dates of collection, two storage temperatures, two foliage drying temperatures) replicated five times giving 60 plots. Each plot comprised 45 cuttings inserted in a propagation tray at 4 cm spacing. Treatments were assessed for rooting percentage and root score (see Experiment 1) on 17 November. All other aspects of propagation practice followed standard procedures (Mason, 1984). Data analysis followed procedures outlined for Experiment 1.

Experiment 5. Precallusing to improve cutting root systems

In the current propagation system (Table 3.1), a percentage of cuttings either fail to root during propagation or do not survive after lining-out. A technique for screening cuttings before insertion which could identify material with low rooting potential would be useful. These cuttings could be culled without being inserted, thus improving success rates. A technique evaluated in Newton nursery in 1985 was that of 'precallusing' whereby cuttings are placed in warm, moist conditions for a short period after collection and only those which produce a rim of callus tissue are inserted.

First and second cycle tip cuttings (8 cm long) were collected on 21 February 1985 from source material of Queen Charlotte Islands origin. Cuttings were allocated at random to either a 'precallusing' or a cold-storage treatment. Precallusing took place in a plant propagator unit (34 × 68 × 10 cm deep) with a transparent perspex cover (30 cm tall). The unit had a 40W heating element in the base under thermostatic control to provide 24 ± 1°C. The base of the tray was filled with a fungicide solution (0.1% thiophonate-methyl) to prevent *Botrytis* and to maintain high humidity in the propagator. Cuttings were placed in bundles of 100 on a layer of plastic mesh suspended 5 mm above the surface of the fungicide. One propagator could hold up to 2000 cuttings. The propagator was kept under natural daylength in a small laboratory heated to 20°C. Cuttings were kept in the propagator for 14 days after collection; any which did not have a small rim of callus tissue at the base were discarded before insertion (*c.* 15% of the total). Cuttings given the cold storage treatment were sealed in clear polythene bags and stored at +1°C for the same period. This length of cold storage has no effect upon rootability of Sitka spruce cuttings (Mason, 1987). In addition to the pretreatment, cuttings were either treated with a rooting hormone (5 second dip in a 500 ppm solution of naphthalene acetic acid/indole butyric acid in alcohol) or left untreated as a control. This treatment was applied before precallusing or after cold storage to ensure that it had maximum effect. Cuttings were inserted on 8 March into a rooting bed with a 4:1 grit (2–3 mm, lime-free):sphagnum moss peat mixture. Half of the bed was warmed by a heating cable providing a minimum temperature of 10–15°C at 5 cm depth, the other half was unheated and was generally 3–4°C less than the heated section.

A randomised block design with eight replicates was used. Plot size was 20 cuttings inserted at 4 cm spacing, Four blocks were sited on the heated and four on the unheated bed so the effect of heating could be explored as an interaction. Ten buffer rows separated the heated and unheated sections. Assessments of percent of cuttings rooted and root score took place at 13 and 20 weeks after insertion when four randomly chosen replicates (two from each of the heating treatments) were harvested. Cuttings were maintained under normal misting regimes for the Newton nursery polyhouse (Mason and Keenleyside, 1988) with liquid fertiliser being applied weekly from 10 weeks after insertion diluted at 400 ppm NPK at a rate of 1 litre solution m^{-2}. Results were analysed using normal analysis of variance procedures with percentages transformed by arcsin if required.

Experiment 6. Low cost propagation

One way of reducing costs would be to root cuttigs in open nursery beds, possibly under tunnel cloches. Similar systems have been used successfully with *Pinus radiata* in New Zealand (Menzies, Faulds and Dibley, 1988). Other experiments had shown that Sitka spruce could be rooted in polyhouses under simple hand-watering regimes (Mason and Keenleyside, 1988).

An experiment in 1986 examined the rooting performance of first cycle cuttings given three different pretreatments and then inserted into sterilised seedbeds covered with cloches that were given a range of ameliorative treatments. The pretreatments were: precallusing for 14 days (as in Experiment 4); cold storage at +1°C for 14 days; and direct insertion without any pretreatment. The main seedbed treatments were the presence or absence of consolidation of the bed with a light roller before insertion. A range of subsidiary treatments compared the effect of incorporating various substrates such as bark or grit into the bed, but these generally proved very unsuccessful and are not discussed further.

The seedbeds were sterilised in September 1985 using dazomet (375 kg a.i. ha^{-1}). The sterilant was released in March 1986 and basal fertiliser was applied at the same time ('Enmag': NPK Mg 5:24:10:16 at 1300 kg product ha^{-1}). The nursery soil at Newton is a sandy-loam with pH of 5.2 and 3.4% organic matter content. Tip cuttings (8 cm long) were collected from 3-year-old plants of Queen Charlotte Islands origin on 25 March for the precallusing and cold storage treatments; cuttings for the direct insertion were collected on 4 April. All treatments were inserted on 9 April. After insertion, the beds were watered and immediately covered by a clear polythene cloche with a green shade.

A split-plot design was used with seven seedbed treatments (i.e. the two consolidation plus five subsidiary treatments) replicated twice to provide 14 main plots; these main plots were randomly split for the three types of pretreatment. Each split plot contained 100 cuttings at 4 cm spacing with 10 cm^2 buffers between subplots and 50 cm^2 buffers between main plots. The experiment was laid out on beds running along a west-east axis. Cloches were finally removed on 17 September when treatments were assessed for percent of cuttings rooted and root score (see Experiment 1).

Results

Experiment 1. Propagation in containers and trays

There were no significant differences between rooting percentage in the standard trays (94.8%) and the shallow and deeper containers (93.1% and 93.6% respectively). However, root score was greater in the trays (6.0) than in either of the containers (5.2 for the shallow; 5.5 for the deep). These differences were highly significant ($p < 0.01$; SED 0.2).

Rooting performance was affected by the vari

Table 3.2 Effect of liquid and basal fertiliser upon the height growth (cm) of Sitka spruce cuttings, 20 weeks (a) and 30 weeks (b) after insertion

		20 weeks (a)		
		Basal fertiliser		
		N	*MP*	*GNT*
Liquid fertiliser	**C**	11.7	13.6	12.2
	HN	11.6	17.3	13.9
	HK	12.4	16.4	13.5
	B	12.0	18.9	12.7
		5% LSD = 2.1		

		30 weeks (b)		
		Basal fertiliser		
		N	*MP*	*GNT*
Liquid fertiliser	**C**	12.6	17.3	15.7
	HN	12.9	16.4	14.7
	HK	13.1	18.4	16.2
	B	12.6	18.6	16.2
		5% LSD = 2.8		

Treatment codes are:

1. Basal fertilisers: N – control; MP – Miniprill; GNT – 'Gold N' plus trace element frit.
2. Liquid fertilisers: C – control; HN – high nitrogen; HK – high potassium; B – balanced.

ous substrates since both rooting percentage and root score were poorer in pure SMP than in the various mixtures. However, these results conform with those found in other experiments (Mason and Keenleyside, 1988; John and Mason, 1987) and will not be considered further, particularly since there was no interaction between substrates and the container/tray treatments.

Experiment 2. Propagation and nutrition in containers

At 20 weeks, cuttings inserted in the substrate containing 'Gold N' had significantly ($p < 0.001$) poorer rooting (91%) than cuttings inserted with 'Miniprill' or the control (97% and 98% respectively). No treatment had any effect upon root score. However, there were interesting effects upon height growth, particularly in the interaction between liquid and basal fertilisers ($p < 0.05$) (Table 3.2a). The combination of liquid fertiliser plus 'Miniprill' significantly improved height growth compared with all other treatments, but neither component on its own had a major effect.

At 30 weeks, average rooting was 98% with no difference between treatments. There were no differences in root score. Significant differences in height growth ($p < 0.001$) were due to taller plants in all treatments with 'Miniprill' basal fertiliser; there was no interaction with liquid fertiliser (Table 3.2b). In addition, only those treatments with incorporated basal fertiliser had average heights exceeding 15 cm.

Experiment 3. Management of stock plants

The size of container had major effects upon stock plant growth ($p < 0.001$; Table 3.3a). Plants in the 1 litre containers were smaller than all other treatments ($p < 0.05$) and those in the 2 litre were smaller than those in the 8 litre ones ($p < 0.05$). Trends in height increment were similar. The only differences in foliage analysis at the end of season were for nitrogen. Levels in the stock plants in 1 litre containers were very

Table 3.3 (a) Effect of stock plant pot size and nutrition upon stock plant height growth, nutrient status, and subsequent rooting and rooting percentage of cuttings

Pot size (litres)	*Fertiliser regime*	*Second year height (cm)*	*Stock plant height increment (cm)*	*Rooting (%)*	*Nitrogen status (% dry weight)*	*Root score*
1	HN	74.0	44.2	94.4	1.17	3.5
	B	75.3	45.7	93.8	1.12	3.4
2	HN	99.3	69.2	99.2	1.49	4.4
	B	82.0	52.7	99.6	1.66	3.9
4	HN	97.7	67.8	97.6	1.68	4.8
	B	104.0	73.7	97.0	1.64	4.1
8	HN	106.3	75.2	97.4	1.96	4.7
	B	106.7	76.3	97.0	1.70	4.1
SED		8.6	8.4	1.8	n/a	0.3

(b) Nitrogen levels (% dry weight) at different dates in shoots of stock plants given different fertiliser regimes (averaged across pot sizes)

Fertiliser	*Date*				
regime	4/86	7/86	8/86	9/86	11/86
HN	2.11	1.61	1.55	1.35	1.58
B	2.05	1.55	1.38	1.21	1.53

Notes: 1. Pot size refers to the size of the container in which the stock plants were grown.
2. HN and B refer to either a high nitrogen or a balanced NPK regime respectively. See text for details.

deficient and increased progressively with a larger size of container. Nitrogen levels during the season (Table 3.3b) showed initial high levels followed by a decline during active extension growth in July and August and a subsequent partial recovery. The high N regime tended to show higher N values than the balanced regime.

Transforming the rooting percentages had no effect upon the analysis so actual values are given in Table 3.3a. The effect of pot size was highly significant ($p < 0.01$) due to the poorer rooting of the cuttings from plants grown in 1 litre containers. There was no difference in rooting percentage between the other pot size treatments. The root score results showed very highly significant effects ($p < 0.001$) of both pot size and fertiliser regime. Cuttings from the 1 litre treatment had lower root scores than the other treatments with no differences between the remainder. The cuttings from stock plants provided with a high nitrogen fertiliser regime showed higher root scores than those given a balanced regime (4.4 against 3.9; SED 0.1).

Other treatment differences were observed during propagation. Thus 7 weeks after insertion over 90% of cuttings from the 4 and 8 litre treatments had fully flushed compared with less than 30% flushed for the smaller sizes of pot (personal communication, A. A. Green, Forestry Commission Research Division).

Experiment 4. Storage of cuttings for summer insertion

There was a very highly significant ($p < 0.001$) three-way interaction between treatments for both rooting percentage and root score (Table 3.4). This interaction for rooting percentage largely reflected considerable month-to-month variation in rootability of cold-stored (+1°C) material depending upon whether it was stored with dry or moist foliage. Thus in January, better results were obtained with moist foliage

Table 3.4 Effect of date of collection, type of storage and foliage drying upon (a) rooting percentage and (b) root score of Sitka spruce cuttings

(a) Percentage[1] of cuttings rooted

	Type of storage			
	Cold storage		*Freezer storage*	
Foliage	*Dry*	*Moist*	*Dry*	*Moist*
Month of collection				
January	12.6	76.5	72.8	60.4
February	14.7	7.0	80.3	62.4
March	79.2	0.0	35.9	51.0
	SED = 6.0			

Note: [1]Values presented are the transformed data. To help interpretation 80.3 = 97.2%; 51.0= 60.4% and 12.6 = 4.7%.

(b) Root score

	Type of storage			
	Cold storage		*Freezer storage*	
Foliage	*Dry*	*Moist*	*Dry*	*Moist*
Month of collection				
January	1.96	4.04	4.10	4.12
February	2.48	1.96	4.44	4.04
March	4.42	0.00	3.58	3.78
	SED = 0.67			

Table 3.5 Effect of propagation cycle, pretreatment and rooting hormone upon the rooting performance of Sitka spruce cuttings (a) 13 weeks and (b) 20 weeks after insertion

		13 weeks (a)			
		Rooting percentage[1]		*Root score*	
Cycle	Hormone	Precallus	Cold Store	Precallus	Cold Store
First	+	96.3	68.8	2.3	1.7
	−	90.0	76.3	2.3	1.5
Second	+	98.8	91.3	2.9	1.5
	−	98.8	83.3	3.1	1.6
SED		11.2		0.3	

		20 weeks (b)			
		Rooting percentage[1]		*Root score*	
Cycle	Hormone	Precallus	Cold Store	Precallus	Cold Store
First	+	100	98	3.8	3.8
	−	100	100	4.1	3.5
Second	+	100	95	4.8	4.3
	−	98	100	5.6	4.3
SED		1.5		0.2	

Note: [1]Actual rooting percentages are presented since there was little difference when data were transformed.

whereas the reverse occurred in March. Results with freezer stored material were less variable, although the March insertion was poorer than the earlier months. Trends in root score were broadly similar to those for rooting percentage.

Despite the interactions, there were also important effects of main treatments. Thus freezer stored cuttings showed significantly higher rooting and root score than cold-stored material (both $p < 0.001$). Cuttings collected in January had significantly ($p < 0.01$) higher rooting percentage than those collected in February or March, and cuttings stored with dry foliage showed a higher rooting percentage than those stored with moist needles ($p < 0.05$).

Experiment 5. Precallusing to improve cutting root systems

Effects of pretreatment, hormone and propagation cycle are shown in Table 3.5. Interactions with bed heating were minor and are not considered. At 13 weeks precallused cuttings had significantly ($p < 0.05$) higher rooting than cold-stored material, but no other differences were significant. At 20 weeks, all treatments showed high rooting percentage.

Root scores of precallused cuttings at 13 weeks were significantly greater ($p < 0.001$) than for cold-stored ones. Second cycle cuttings produced higher root scores ($p < 0.05$) than first cycle due to an interaction ($p < 0.05$) between propagation cycle and pretreatment with second cycle cuttings responding more to precallusing. Root score at 20 weeks showed major effects of pretreatment and propagation cycle (both $p < 0.001$). Second cycle scores were higher than first cycle ones. The scores of precallused cuttings were more than those of the cold-stored ones. The interaction ($p < 0.01$) between cycle and pretreatment was again due to the greater response of second cycle cuttings to precallusing. There was also another significant ($p < 0.05$) interaction because of the greater response of second cycle cuttings to precallusing in the absence of hormone.

Experiment 6. Low cost propagation

When the cloche was removed, it was noted that the southern side had dried out more, resulting in poorer rooting. Rooting percentage was significantly ($p < 0.05$) higher in unconsolidated soil than in the normal bed (48.3% compared with 26.7%; SED 7.6). Rooting was also improved by precallusing which was significantly ($p < 0.01$) higher than for either no pretreatment or cold storage (51.5%, 27.5% and 33.5% respectively; SED 2.5). The highest rooting achieved (62%) was by combining precallusing with insertion into an unconsolidated bed. There were no significant differences between treatments for root score although precallused cuttings again had higher root scores (3.5 compared with 3.0 and 3.1 for controls and cold-stored cuttings).

Discussion

These results indicate that there are a number of possible alternatives to the basic propagation system. For instance, Sitka spruce cuttings can be rooted in containers (Experiment 1) although an intensive fertiliser regime combining basal and liquid top-dressing is required if usable plants are to be produced in one year (Experiment 2). Not all basal fertilisers will be equally effective as shown by the improved performance of the 'Miniprill' as compared to the urea-based 'Gold N'. These results concur with experience in Scandinavia where Norway spruce (*Picea abies* (Karst.) L.) cuttings are also rooted in containers (Kleinschmit, 1992) although 18 months are required to produce a usable plant after inserting in August. The attraction of rooting cuttings in containers is that the labour-intensive transplanting operation is eliminated and the need for growing space in the bare-root nursery is reduced.

The successful rooting after 6 months freezer (−1°C) storage (Experiment 4) makes it possible to produce two crops in one growing season. The variable results from cold storage (+1°C) indicate that cuttings may deteriorate when stored for long periods at temperatures above 0°C, presumably because of factors such as respiration and fungal activity. However, cuttings destined for freezer storage should be collected before shoots have started to deharden in late winter. Under normal winter conditions in

Britain, this would require collection before mid-February. Racey, Cameron and Leverlie (1986) and Behrens (1984) also report on the successful use of subzero storage with conifer cuttings, though the periods were less than the 6 months reported here. Another attraction of freezer storage is the fact that cuttings can be inserted in summer in warm conditions favouring root initiation, yet using dormant material that will withstand large-scale handling. This approach could be combined with insertion in containers to produce a 25–35 cm plant in 18 months for use on restock sites.

Major aims in propagation are to improve both the speed of rooting and the root volume. The precallusing technique appears promising for both reasons since pretreated cuttings had higher rooting percentage and root score after 13 weeks (Experiment 5) and performed better when inserted in nursery soil (Experiment 6). Speeding up the initial phase of root initiation by maintaining cuttings in a warm, high humidity propagator before insertion in a mist house reduces the period of risk before the development of independent root systems. The technique can also be used to screen out poor quality cuttings, assumed to be those which do not produce any callus during the period in the propagator. This could be particularly useful where cuttings are inserted in containers since it is important that each cell should produce a usable plant. The superior rooting of second cycle cuttings (Experiment 5) is thought to be an artefact induced by fertiliser regimes given to the source plants since these are known to affect rooting ability (Kleinschmit, 1973; Mason and Keenleyside, 1988).

The quality of Sitka spruce cuttings can be influenced by appropriate stock plant management. Nitrogen is recognised as an important nutrient for both root initiation and subsequent root development (Blazich, 1988). The poorer performance of cuttings from stock plants grown in 1 litre containers presumably reflected their N deficient status at insertion. By contrast, cuttings from stock plants grown in larger containers gave better rooting in line with an improved N status. The results from the two stock plant feeding regimes were less clearcut, since there was no effect upon rooting percentage, but the high nitrogen regime produced cuttings with greater root scores although end of season N status was very similar. Inspection of the data (Table 3.3b) suggests that the high N regime maintained better foliage concentrations throughout the season. It would appear that successful stock plant management requires the maintenance of adequate nitrogen levels at all times during the year before cuttings are collected.

Attempts at rooting Sitka spruce in tunnel cloches in open nursery beds (Experiment 6) were moderately successful. Higher rooting could probably have been obtained if the beds (and cloches) had been laid out north-south to reduce solar radiation levels. A further improvement would be to incorporate some form of irrigation within the cloche to maintain humidity. It was important not to consolidate the beds, possibly because compaction reduced the aeration of the soil at the base of the cutting and restricted subsequent root development. The system has been shown to be operationally feasible at Tilhill nursery (personal communication, R. F. Sym, Tilhill Nurseries Division).

Implications for costs

Estimates given in Table 3.6 show how various modifications to the standard propagation system might reduce production costs. It should be stressed that the savings discussed are only indicative.

Procedure 1 allows for the real possibility of improving the output of the standard system. Raising the rooting performance and survival rate of second cycle cuttings to that of first cycle cuttings could save around £10 per 1000 rooted cuttings. This should be attainable since correct fertilisation of source plants has been shown to eliminate differences between cycles (Mason and Keenleyside, 1988). Further improvements could be made if rooting and survival of cuttings from both cycles was raised to 95% together with a reduction in culling percentages at lifting. Experimental evidence presented above shows that such targets are not impossible, although a precallusing facility may be required to screen cuttings before insertion. It is not

Table 3.6 Possible reductions in production costs of Sitka spruce cuttings by using alternative or amended propagation systems

System	*Cost saving £/1000 plants*	*Notes*
1. Improve rooting and outturn of present system (see Table 3.1)	10–30	Higher figure assumes precallusing
2. Containerise second cycle cuttings	15–20	No improvement in rooting assumed
3. As System 2 but with improved rooting	20–40	Precallusing included
4. As System 3 but also with automated insertion	20–60	Costs of automation are speculative
5. Outdoor insertion in covered nursery beds	0–40	Depends upon rooting success. Second cycle only

Notes:
1. See text for further details.
2. No allowance for double cropping by use of freezer storage.

known how much such a facility might cost.

Procedure 2 assumes that second cycle cuttings are inserted in containers so that transplanting costs are eliminated, but no improvement in rooting is implied. Transplanting costs and subsequent maintenance of second cycle cuttings can make up 15–30% of the costs considered in Table 3.1. However, these gains are offset by the greater cost of the containers, a reduction in the number of cuttings inserted per unit area and a greater volume of propagation medium required.

Procedure 3 implies that precallusing is used to improve rooting success to between 90 and 95% of cuttings inserted. This goal should be feasible given the evidence of Experiments 2 and 5.

Procedure 4 is extremely speculative and assumes that machinery is available to allow for automated insertion of cuttings. This would reduce the labour input in both first and second cycles and could result in a 5–15% reduction in costs depending upon the capital and operating cost of the machinery.

Procedure 5 by contrast adopts a 'low tech.' approach, assuming a target of 70% rooting and 75% usability of rooted second cycle cuttings. It is conceivable that insertion could be mechanised in conjunction with normal lining-out machinery. The success of this system will depend upon correct manipulation of the seedbed to provide optimum rooting conditions. The use of freezer storage is not considered in these estimates, because it is best seen as a way of reducing capital investment in polyhouses as well as of spreading labour requirements.

Conclusion

Despite the preliminary nature of these costings, the experimental evidence suggests it should be possible to produce Sitka spruce cuttings more cheaply. The key factors appear to be the control of cutting quality so that outturn of usable plants is maximised and the reduction of non-essential labour elements such as transplanting. Containerisation may be of increasing importance in this plant production system as a means of reducing labour costs. This may also have benefits for growth after planting (Mason and Sharpe, 1992). The fact that all systems show some potential for reducing costs indicate that we may expect the price of cuttings to come closer to that of normal seedling planting stock.

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Appendix 3.1 Standard two cycle propagation system for Sitka spruce

Stage	*Year*	*Month*	*Operation*
1	0	February/March	Seed stratification
2	0	March/April	Sow seed
3	0	April–July/Aug.	Germinate and grow on seedlings
4	0	July/August	Pot up seedlings for stock plants
5	0–1	August–May	Grow on stock plants
6	1	May	Pinch out leaders and side shoots of stock plants to promote branching
7	1	May/June–Sept.	Stock plant management (target is plants up to 100 cm tall)
8	1–2	October–Feb.	Overwintering stock plants
9	2	February/March	Prepare to collect first cycle cuttings
10	2	February/March	Collect first cycle cuttings
11	2	March	Insertion of cuttings
12	2	March–June	Propagation of cuttings

One seed sown per cell in containers (100–200 cc cell capacity). Container substrate is sphagnum moss peat : vermiculite 3 : 1 by volume with Ficote 70 (NPK : 16 : 10 : 10) at 1.5 kg m^{-3}, ground limestone at 1 kg m^{-3}, magnesium limestone at 2 kg m^{-3} and fritted trace elements at 0.3 kg m^{-3}.

Maintain seedlings in a polythene greenhouse under natural daylength at target temperatures of 20/15°C day/night with permitted maxima/minima of 30/5°C. Supplementary weekly liquid feeding using balanced NPK at 200 ppm N will be necessary in July and August.

This should be done when seedlings are about 15 cm tall. Pot seedlings into 4 litre containers with substrate of: sphagnum moss peat : ground pine bark : grit in 6 : 3 : 1 ratio by volume. Incorporated basal fertiliser of Osmocote NPK 18 : 11 : 10 (8–9 months) at 3 kg m^{-3}, ground lime at 1.2 kg m^{-3}, magnesium limestone at 2.4 kg m^{-3} and fritted trace elements at 0.3 kg m^{-3}. The role of the bark is to keep the substrate open and to provide a buffer against sudden release of nutrients in high temperatures. No liquid feeding should be required until May/June of year 1.

Maintain stock plants in unheated polythene greenhouses overwinter. Keep plants spaced out so that laterals do not touch.

This is best done with the fingers to prevent damage. Any plants of poor form should be culled out.

Feed up to twice weekly throughout the period of active growth (late May–August) using a high N product (e.g. NPK 2:1:1) at 200–250 ppm N. Change to balanced (NPK 1:1:1) weekly feeding at 200 ppm N in September and October. Feed to runoff to ensure that substrate is at correct nutrient balance. Target nitrogen level in foliage should be 1.5% dry weight. Use a conductivity meter for monitoring leachate. Water plants regularly (i.e. daily) especially during warm conditions. Replace plants at intervals to ensure laterals do not touch and cutting quality is maintained.

Can be done either in a frost free polyhouse or plants can be overwintered outside. If the second option is taken, the plants must be transferred outside before October to guard against early frosts. Roots may have to be protected against freezing temperatures.

Spray all plants with a systemic fungicide (e.g. 0.1% thiophanate methyl) 14 days before collection to guard against *Botrytis*.

A standard length of 8 cm ± 2 cm is used. Both tip (with terminal bud) and base (with no terminal bud) cuttings are collected. Only collect from wood laid down in the previous year (i.e. year 1). Minimum diameter of cuttings should be *c.* 2 mm (i.e. cuttings should withstand gentle bending between thumb and forefinger). Keep cuttings cool and shaded after collection. They can be cold-stored (1°C) in polythene bags for 2-3 weeks without damage.

Insert to 3 cm depth in seed trays or similar that are 7 cm deep. Ideal spacing between cuttings is 4 cm, but 3 cm is acceptable. Seed trays should be placed on rooting benches or on fine sand. This prevents waterlogging at the base of the medium. Substrate should have an air filled porosity of >15%. Sphagnum moss peat : pine bark : grit (2–3 mm) or perlite in a 1 : 1 : 1 ratio by volume is our preference, but other alternatives are acceptable if they provide support and maintain good drainage. No rooting hormone is applied before insertion; stripping of basal needles is also unnecessary. No basal fertiliser is incorporated in the substrate.

Rooting trays are placed in a mist propagation unit under natural daylength. A white polythene cover or other shading is desirable to diffuse direct sunlight and reduce the risk of scorch. Target relative humidity levels are 90–95% during daylight hours. Peak misting frequency is a 5 sec burst every 1–2 minutes. Mist frequency should be controlled by a device linked to ambient evaporative demand. Use fan ventilation to keep temperatures <30°C. Fans should have moist pads on the outside to prevent dry air being sucked into the house. Fungicides are applied weekly in rotation to prevent *Botrytis* attack. Apply fungicides (and fertilisers) under dull conditions or in late evening to avoid scorch. Switch off the mist for 6–12 hours after application. Start of callus initiation at base of cuttings 6–10 weeks after insertion.

Appendix 3.1 Standard two cycle propagation system for Sitka spruce *continued*

Stage	*Year*	*Month*	*Operation*
13	2	June/July	Weaning of cuttings
14	2	July/August	Lift and line-out cuttings
15	2/3	August–May	Care for lined-out cuttings
16	3	May–October	Maintenance of lined-out cuttings (target is plants 40–50 cm tall)
17	3/4	October–Feb.	Overwintering of cuttings
18	4	February/March	Collect second cycle cuttings
19	4	March–July/Aug.	Propagation and weaning of second cycle cuttings
20	4	July/August	Line-out second cycle cuttings
21	4/5	August–May	Maintenance of lined-out cuttings
22	5	May–October	Culturing of cuttings for forest planting (target is plants 25–35 cm tall)
23	5/6	Nov–March	Lifting of cuttings, grading and dispatch
24	6	Spring	Forest planting

Notes: 1. Mention of commercial names is for information only and does not represent an endorsement.

2. An alternative stock plant regime is to replace stages 4–8 inclusive with one where the stock plants are potted on in outdoor raised beds. These beds are 30 cm high and 1 m wide with a substrate of Sphagnum moss peat : composted pine bark : grit in 1 : 1 : 1 ratio by volume. 16–18 month Osmocote (NPK Mg: 16:9:9:3) is added at 4–6 kg m^{-3} ground limestone at 3.0 kg m^{-3} and trace element frit at 0.3 kg^{-3}. Plants are spaced at 25 cm within and between rows. Target stock plant height is 50–75 cm. This system will give a lower yield of cuttings (30–40 per plant) compared with the standard polyhouse regime (60–70+ per plant) but it is less demanding on maintenance, especially watering.

Comments

After 50–70% of the crop has root initials, mist frequency should be reduced at weekly intervals until only one or two waterings per day are required. Burst length is increased so that there is a 'watering' rather than 'misting' regime. Raise trays of rooting beds to promote air pruning and encourage root proliferation within the tray. Start liquid feeding once weaning has begun to counteract nutrient leaching during propagation. Use a balanced NPK feed at 200 ppm N applied at 4 litres solution m^{-2} twice a week. Weaning is near completion when white fleshy roots ('water roots') have been transformed into brown fibrous roots which will withstand transplanting.

Cuttings should be lined-out in a bare-root nursery using standard lining-out machinery. Space at 10 cm (50 plants m^{-2}) within rows to encourage branching. Apply normal basal fertilisers before lining-out. Discard any poorly rooted or misshapen cuttings before lining-out.

Lining-out should occur early enough so that cuttings make new root growth to guard against risk of autumn frost lift. Normal herbicide regimes after lining out.

Apply a balanced 1 : 1 : 1 feeding regime to provide around 100 kg of elemental N ha^{-1} over the growing season. If possible apply little and often to maximise height growth and yield of second cycle cuttings.

Attempt to collect as many tip cuttings as possible to guard against double-leadering risks from base cuttings.

Regimes are identical to first cycle.

As for the first cycle except that spacing is now 5 cm (approx. 100 plants m^{-2}).

As for first cycle.

One-two light top dressings of N (25 kg elemental N ha^{-1} in total) before undercutting at 8 cm in July. Follow by fortnightly or three weekly wrenching until end of growing season. Apply additional N and K to maintain nutrient status. Total of 50–75 kg of elemental N ha^{-1} over season.

Remove any double leadered plants. Plants with slight (up to 15–20° deviation from vertical) stem bend are acceptable. Otherwise treat as normal forest planting stock.

Paper 4

The establishment and silviculture of Sitka spruce cuttings

W.L. Mason[1] and A.L. Sharpe[2]
[1]Silviculture (North) Branch, Forestry Commission, Northern Research Station, Roslin, Midlothian, EH25 9SY, UK.
[2]Silviculture (North) Branch, Forestry Commission, Research Division, Newton Nursery, Elgin, Morayshire, IV30 3XR, UK.

Abstract

Existing silvicultural guidelines for the use of Sitka spruce cuttings are reviewed in the light of a number of recent experiments on provenance mixtures and various aspects of establishment of cuttings.

Provided first and second cycle material is used, improved Sitka spruce cuttings may be planted pure or in line mixtures. Ten years after planting, transplants of faster growing Queen Charlotte Islands (QCI) origins were 50% taller than Alaskan origins. Pattern of provenance mixture (alternate rows or alternate plants within the row) had no effect on survival and height growth. Cuttings and transplants of the same QCI origin had similar survival, height and diameter after 10 years. However, half-sibling cuttings of a genetically improved family were around 10% better in height growth than the QCI material. When half-sibling cuttings of three propagation cycles were compared with seedlings of the same family and with QCI transplants, first cycle cuttings were the most vigorous in terms of height growth and there tended to be a slight decline in vigour with increasing cycle. A comparison of tip and base cuttings of two families showed major differences between families for height and form but little effect of cutting type.

Cuttings should be graded using normal plant quality standards except that some allowance should be made for slightly more sinuous stem form in the cuttings. This difference in stem form normally disappears within 1 or 2 years after planting. Three years after planting, improved cuttings from research and commercial nurseries generally showed greater vigour than QCI transplants. However, a batch of containerised cuttings proved sensitive to establishment conditions, showing good growth on cultivated ground with minimal weed competition, but poorer growth and survival on an uncultivated site with weed competition. Generally, standard silvicultural practices can be used in the establishment and management of plantations of cuttings. However, they should be planted on fertile sites of low windthrow risk so that the benefits from improved growth can be maximised.

Introduction

About 1.5 million cuttings of genetically improved Sitka spruce were planted in British forests during the 1988/89 planting season. This figure is expected to rise during the 1990s as more cuttings become available and as more managers are attracted by the prospect of improving the quality and yields from their forests. However, it is important that cuttings should be planted on the most appropriate sites and that they should be managed with the best silvicultural practices if the maximum benefit is to be obtained from the use of this new and expensive planting stock.

A number of provisional guidelines have been provided for managers interested in planting Sitka spruce cuttings (Mason and Harper, 1987). These are: that cuttings should be planted on sites in northern Britain for which Queen Charlotte Islands (QCI) origins would normally be chosen; that these sites should not be prone to windthrow (i.e. of a low Windthrow Hazard Class; Miller, 1985) so that stands would generally be thinned and grow for a full rotation; that stands of unimproved QCI origin growing on these sites would produce at least Yield Class 12 (12 m^3 ha^{-1} yr^{-1} maximum mean annual increment, Edwards, 1981); that cuttings should be planted in a 2 : 1 mixture with unimproved stock; and that cuttings should be handled, planted and subsequently managed with the attention appropriate to expensive, high yielding material.

Some of these guidelines are examined elsewhere in this volume (Fletcher, 1992; Lee, 1992). This paper presents results about the use of different types and qualities of cuttings and about the development of mixtures of Sitka spruce. The opportunity is taken to update results from published experiments on the potential of containerised cuttings (Mason, in press). New information is provided on the comparative performance of tip and base cuttings and of cuttings from different propagation cycles. These findings are used to provide a comprehensive set of silvicultural recommendations for managers interested in the use of Sitka spruce cuttings.

Materials and methods

Experiment 1. Mixtures

The experiments in Britain with mixtures of Sitka spruce cuttings and transplants are not sufficiently old to provide reliable comparative data. However, some information on the effect of mixing a faster and slower growing crop of Sitka spruce can be extrapolated from an experiment that compares the growth of QCI and Alaskan origins of Sitka spruce when planted in three different patterns of mixture. The objectives were to see how soon the faster growing QCI origin dominated the slower growing Alaskan one, to examine how this was affected by the pattern of mixture, and, in the long term, to see which of these 'self-thinning' mixtures (Lines, 1981) provided a more stable stand. Pure QCI control plots were also included.

This experiment was planted in May 1979 on a peaty gley soil in Moffat Forest (Borders Region; 55° 25'N). The site is 360 m a.s.l. with an annual rainfall of 1400 mm. The experimental area was ploughed before planting using a double mouldboard plough with a single tine on previous twin tine ripping (D45/T60/t on –/DT60/t; Thompson, 1978). The experimental treatments were: QCI and Alaskan origins mixed as alternate pure rows; the same origins mixed by alternate plants in all rows; a 3 : 1 mixture of QCI and Alaskan origins with pure rows of QCI alternating with rows of the two origins mixed by alternate plants; and pure plots of QCI origin. QCI plants were from a seed collection in Culloden Forest from a stand of QCI origin (identity 74(2004)); the Alaskan plants were from an imported seed lot from the Outer Isles, Alaska (identity 69(7986)).

These four treatments were replicated three times in a randomised block design with a plot size of 100 plants in a 10 × 10 plant layout. Failures were replaced in 1981 and 1982 to provide 100% stocking. Chemical weed control and normal fertilisation for the site (unground rock phosphate at 375 kg ha^{-1}) were routinely applied by hand to all plots during the establishment phase. Assessments of survival were carried out up to 6 years after planting and height growth was measured at 3, 6 and 10 years. Results were analysed using normal analysis of variance procedures.

Experiments 2 and 3. Quality of rooted cuttings

A major concern in any propagation programme is to show that cuttings can survive and grow in the forest as well as equivalent transplant stock. It is also important to see how comparative performance is affected by features such as variation in plant quality. Two experiments were established to examine the effect of poor form of cuttings (e.g. distorted or multiple leaders) upon growth and survival in comparison with cuttings of good form and transplants of the same origin.

The first experiment was planted in February 1980 in Craigellachie Forest (Grampian Region; 57° 20'N); the site was a stony ironpan soil with severe exposure at 290 m a.s.l. and 880 mm annual rainfall. The experiment was completely ploughed before planting (2S45/T60/t; Thompson, 1978) and fertilised with unground rock phosphate at 375 kg product ha^{-1} in June 1980. Nitrogen was applied to the whole experiment in 1986 (urea at 350 kg product ha^{-1}). Experimental treatments were: CQG – good quality cuttings; CQP – poor quality cuttings; T2 – 2-year-old transplants (1+1); T3 – 3-year-old transplants ($1^1/_2+1^1/_2$). The T2 plants were of identity 72(7111) from East Graham Islands, QCI; all other treatments were of 70(7111), also from East Graham Islands. Cuttings were propagated as $C^1/_2+1^1/_2$ stock (Samuel and Mason, 1988) from 3-year-old transplants (2+1) using standard techniques (Mason, 1984).

The poor quality cuttings were typified by truncated or distorted leader growth as a result of *Botrytis* damage during propagation. A randomised block design with four replications of the four treatments was used. Plot size in three blocks was 11 × 11 plants at 2 m spacing and in the remaining block it was 20 × 20 plants. A central assessment plot of 9 × 9 or 12 × 12 plants was used depending upon the block. Height was assessed at planting and at 1, 3, 6, and 10 years after planting as was percentage survival. Diameter at breast height (1.3 m) was assessed at 10 years. Stem straightness was measured at 1 and 5 years after planting using a scoring system (1–5; vertical growth to horizontal); this parameter is described as 'form'. Results were analysed using normal analysis of variance procedures with survival data being transformed by arc sine.

The second experiment was sited in Strathyre Forest (Central Region; 56° 10'N) at 230 m a.s.l. on an upland brown earth – ironpan soil intergrade with an annual rainfall of 1525 mm. Planting took place in April 1980; the site had been ploughed 14 months earlier using a single mouldboard plough (S45/T60/t; Thompson, 1978). Phosphate was applied in 1981 at the same rate used as at Craigellachie (no subsequent nitrogen was needed). Two treatments were added to those used at Craigellachie; C492G – good quality cuttings derived from ortets of the plus tree family 71(4920P); C492P – poor quality cuttings of the same family. Ortets of this family were 2 years old when the cuttings were taken. Other propagation and experimental details were identical to those at Craigellachie. A randomised block design with four replications was used; plot size varied from 125 to 150 plants with a central assessment plot of 7 × 7 plants. The assessment procedure followed that used at Craigellachie except that form was measured 2 and 5 years after planting.

Experiments 4 and 5. Containerised cuttings

Two experiments were planted on restocking sites in Speyside (Grampian Region; 57° 25'N) and Corris (Powys; 52° 35'N) forests to compare the performance of cuttings produced by commercial growers with those produced by research nurseries. The three batches of commercial cuttings were coded P1–P3 and the two batches of research cuttings R1–R2. Three-year-old QCI transplants (T) were included as a standard. Treatments R1, R2, P3 were propagated from one improved seed lot and P1, P2 from another, but differences in genetic gain between these seed lots were minor. All cuttings were produced as bare-root stock except for treatment P2 which were C1+0 containerised cuttings (see Samuel and Mason, 1988 for nomenclature). Treatments R1, R2 and P3 were produced as $C^1/_2+1^1/_2$ cuttings whereas treatment P1 was grown as C1+0 stock (i.e. the cuttings were lifted direct from rooting beds and planted as bare-root stock).

The Speyside experiment was planted in February 1987 upon a podzolic soil overlying induration at 120 m a.s.l. and 800 mm annual rainfall. The site had been ploughed 12 months before planting using a single mouldboard plough (S60/T90/m; Thompson, 1978). Unground rock phosphate was applied four months after planting at a rate of 450 kg product ha^{-1}. The Corris experiment was planted in March 1987 upon an upland brown earth intergrade soil at 305 m a.s.l. with 1200 mm annual rainfall. The trees were planted upon areas of soil from which all vegetation had been removed mechanically ('screefs'). In both experiments, trees were sprayed overall with insecticide (gamma HCH at 0.125% solution) post-planting to guard against *Hylobius* damage.

In both experiments, a randomised block design with five replications was used with a plot size of 25 plants. Height was measured at planting, and height, survival and form (scored as for experiment 2) were assessed at 1 and 3 years after planting. Survival data were transformed by arc sine before analysis. Results at the end of the first year including Root Growth Potential (RGP) measurements have already been presented (Mason, 1991).

Experiments 6 and 7. Effects of propagation cycle

A possible concern with the use of cuttings is that potential genetic gain is attenuated as the source material becomes chronologically older, for instance through the use of cuttings from different propagation cycles (e.g. St Clair, Kleinschmit and Svolba, 1985). Two experiments were planted in the spring of 1984 to examine the comparative performance of seedlings and cuttings of first, second and third propagation cycles of the half-sibling plus-tree family 71(4920P) (treatments are termed 492/S; 492/1; 492/2; and 492/3 respectively).

Two-year-old (1+1) and 3-year-old ($1^1/_2+1^1/_2$) transplants of QCI origins were included for comparison. Cuttings were propagated as $C^1/_2+1^1/_2$ bare-root stock using regimes described by Mason (1984). The 492/S seedlings were produced as 1+0 containerised seedlings in F508 Japanese paper pots (5.1 cm wide × 7.5 cm deep; volume 124 cc; Hollingsworth and Mason, 1989) with the paper being removed from the containers before planting.

The experiments were located at Craigellachie and Glentress Forests (Grampian and Borders Regions respectively; 57° 20'N and 55° 45'N). The Craigellachie experiment was planted in April on an afforestation site on an upland brown earth soil at 200 m a.s.l. with annual rainfall of 900 mm. The site had been ploughed in October 1982 with a single mouldboard plough (S45/T60/m; Thompson, 1978). Grass regrowth was controlled by preplanting herbicide application (propyzamide at 1.5 kg a.i. ha^{-1}). Unground rock phosphate was applied at 375 kg product ha^{-1} one month after planting. The Glentress experiment was sited on a surface water gley soil in an experimental reserve at 290 m a.s.l. with 925 mm annual rainfall. Treatments were planted in late March 1984 on the site of a previous experiment felled in 1983. Glyphosate was applied overall in October 1983 (3 litres product ha^{-1}) to control weed growth. Phosphate was applied at the same time as at Craigellachie.

At both sites a randomised block design with 10 replicates of the six treatments was used. Plot size was eight plants at 2 m spacing. Treatments were assessed for height at planting and, together with survival, at 1, 3 and 6 years after planting. At 6 years after planting, both basal diameter and diameter at half-tree height were measured. A stem form factor was calculated as the ratio of the latter divided by the former. The less the taper on the stem, the closer this factor was to 1.0. Results were analysed in the same way as in experiments 2 and 3.

Experiments 8 and 9. Tip and base cuttings

Current propagation systems rely upon the production of both tip (with a terminal bud) and base (with no terminal bud) cuttings to achieve desired multiplication rates (Mason, 1992). Some cuttings dispatched for forest use may therefore be derived from base cuttings and some growers have suggested that such material might not be as vigorous as tip cuttings.

Two experiments were established in 1985 in Speymouth and Glentress Forests to examine this possibility. Both experiments compared tip (T) and base (B) cuttings propagated as $C^1/_2+1^1/_2$ stock from two half-sibling families; 71(4920P) and 69(9800P). The four treatments were combined in a 2^2 factorial design replicated six times using 10 plant plots. Treatments were assessed for height at planting and for form (scored as for experiment 2), survival and height at 1 and 3 years after planting. Data analysis followed procedures outlined for experiment 2.

The Speymouth experiment was planted in April 1985 on a site immediately beside experiment 4. Site details and all other aspects of experimental management were similar to that experiment. The Glentress experiment was also planted in 1985 close to experiment 7 and received similar management.

Results

Experiment 1. Mixtures

At 6 years, survival of plants from both provenances averaged 98–99% with no difference between treatments. Height growth at 10 years was analysed in two stages. Firstly, an average height was calculated for each plot by combining the values for trees of the two origins. There were significant differences ($p < 0.01$) between treatments which were predominantly due to the lesser height of the two 1 : 1 mixtures when compared with the QCI control (Table 4.1). The height of the 3 : 1 mixture was intermediate between the pure QCI and the two 1 : 1 mixtures, and the latter did not differ significantly from one another. Since the difference appeared to be due to the relatively smaller size of the plants of Alaskan origin, the height growth of plants of the two origins was compared in the 1 : 1 mixtures, assuming that each plot of this mixture was a replicate of two origin treatments. This analysis showed major differences ($p < 0.001$) between treatments with mean height of the QCI and Alaskan origins being 3.16 m and 2.17 m respectively (SED 0.06). This 46% difference in height is broadly similar to the differences at 3 and 6 years after planting (54% and 52% respectively).

Experiments 2 and 3. Quality of rooted cuttings

In both experiments, there were highly significant ($p < 0.01$) differences between height of treatments at planting (Table 4.2). However, there was no significant effect of using planting height as a covariate so the results in Table 4.2 considered below refer to the unadjusted data. Analysis of transformed survival data showed no difference from untransformed data so actual percentages are presented in Table 4.2.

At Craigellachie, there were no significant differences between treatments after 10 years for height and survival. Differences in dbh were not significant although that between the good quality cuttings and either the poor cuttings or the 3-year-old transplants was close to significance. There were also no differences in height increment from years 6 to 10. The initial significant ($p < 0.01$) difference in stem form between the poor quality cuttings and the two transplant treatments had disappeared by year 5 when all treatments had similar upright growth.

There were also no differences in survival at Strathyre although the experimental average was about 15% less than at Craigellachie. However, there were significant differences in height, diameter and height increment ($p <$ 0.001, < 0.001, and < 0.01 respectively). The differences in height and diameter were mainly due to the poorer performance of the 2-year-old transplants (T2) and the poor quality QCI cuttings (CQP). For both parameters, the best achievement was with the family 492 cuttings treatments. Indeed both treatments of this family had significantly better height increment than the other treatments with little difference between the remainder. The cuttings treatments and particularly the CQP plants generally had poorer form than the transplants 2 years after planting, but these differences had largely disappeared after 5 years.

Table 4.1 Effect of mixing QCI and Alaskan (AL) origins in varying proportions upon mean plot height at 10 years

Treatment	Pure QCI	3 QCI 1 AL Row	1 QCI 1 AL Row	1 QCI 1 AL Plant	5% LSD
Height (m)	3.14	2.93	2.65	2.69	0.24

Plant = alternate plants mixed in each row.
Row = plants of each origin in alternate pure rows.

Table 4.2 Survival, height and diameter growth and form of cuttings and transplants of Sitka spruce planted in two separate experiments; data are for 10 years after planting unless stated

Craigellachie

	CQG	*CQP*	*T2*	*T3*	*5% LSD*
Height at planting (cm)	29.8	19.5	15.0	29.4	2.7
Height (m)	3.8	3.6	3.6	3.6	0.4
Height increment year 6–10 (m)	1.5	1.5	1.5	1.3	0.3
Survival %	94.8	96.8	95.8	97.5	6.5
DBH (cm)	7.2	6.4	6.5	6.4	0.9
Form assessment a.	1.6	1.9	1.4	1.4	0.4
b.	1.2	1.2	1.1	1.2	0.1

Strathyre

	CQG	*CQP*	*C492G*	*C492P*	*T2*	*T3*	*5% LSD*
Height at planting (cm)	22.6	13.2	25.4	18.0	11.8	22.7	3.8
Height (m)	4.1	3.6	4.5	4.5	3.8	4.2	0.4
Height increment year 6–10 (m)	2.6	2.4	2.8	2.8	2.4	2.5	0.2
Survival %	79.7	68.7	84.2	82.0	74.5	86.0	16.5
DBH (cm)	8.3	7.1	8.7	8.5	7.2	8.4	0.7
Form assessment a.	1.9	2.2	1.9	1.9	1.8	1.7	0.2
b.	1.6	1.6	1.4	1.5	1.6	1.4	0.2

Notes:
1. Treatment codes are: CQG – good quality cuttings of QCI origin; CQP – poor quality cuttings of QCI origin; C492G - good quality cuttings from family 71(4920P); C492P – poor quality cuttings from family 71(4920P); T2 – 2-year-old transplants; T3 – 3-year-old transplants.
2. Form a. and b. were assessed at 1 and 5 years and 2 and 5 years after planting at Craigellachie and Strathyre respectively.

Experiments 4 and 5. Containerised cuttings

As a result of significant differences in height at planting (Table 4.3), this parameter was tested as a covariate but proved to have no effect. Transformation of survival data was unimportant in the Speyside experiment so actual percentages are presented. However, at Corris the transformation was important and the transformed results are considered below.

At Speyside, all treatments had more than 90% survival after 3 years with no significant differences occurring. There were also no significant differences in stem form with all treatments showing upright growth. Height growth after 3 years showed major differences ($p < 0.001$) with the containerised P2 being markedly superior and the transplants (T) and 1-year-old bare-root (P1) cuttings being much poorer. The containerised cuttings produced greater height increment than all other treatments ($p < 0.01$) with the R2 cuttings being superior to the transplants and P1 cuttings.

There were significant differences in survival at Corris ($p < 0.01$), reflecting lower survival of the P1 and P2 treatments and higher survival of the R1 and P3 ones. Height growth after 3 years and height increment again revealed major differences ($p < 0.001$ for both parameters). Treatments could be divided into three groups for height growth with P3 tallest, R1 and R2 intermediate, and transplants, P1 and P2 being the smallest. Height increment was greatest in P3, but there was an overlap between the intermediate and smallest groups although the order remained the same. There were again no differences in stem form at the Corris experiment.

Table 4.3 Comparative performance of QCI transplants and five different batches of improved cuttings 3 years after planting

Speyside	*T*	*R1*	*R2*	*P1*	*P2*	*P3*	*5% LSD*
Height at planting (cm)	21.8	31.4	28.7	19.8	12.6	31.4	2.0
Survival (%)	96.0	97.6	97.6	92.8	98.4	92.8	6.1
Height (cm)	76.6	95.4	98.7	75.3	106.4	92.5	11.8
Height increment years 0–3 (cm)	54.8	63.9	70.0	55.6	93.8	61.2	11.0
Form assessment	1.4	1.4	1.5	1.5	1.3	1.3	0.2
Corris	*T*	*R1*	*R2*	*P1*	*P2*	*P3*	*5% LSD*
Height at planting (cm)	17.4	32.3	29.5	17.5	14.0	34.6	2.7
Survival (%)	88.8^{bc}	93.6^{c}	91.2^{bc}	77.6^{ab}	72.0^{a}	97.6^{c}	(13.1)
Height (cm)	72.5	101.9	96.7	70.8	74.7	117.1	11.1
Height increment years 0–3 (cm)	55.1	69.6	67.1	53.3	60.6	82.5	10.6
Form assessment	1.2	1.2	1.3	1.2	1.2	1.1	0.1

Notes: 1. All data are for 3 years after planting unless stated.

2. Treatment codes are: T – transplants; R1, R2 – cuttings from research nurseries; P1, P2, P3 – cuttings from commercial production nurseries. P2 are containerised cuttings. See text for more details.

3. In the Corris data, actual percentage values are given, but 5% LSD are for the transformed values and superscripts denote significant differences.

Experiments 6 and 7. Effects of propagation cycle

Despite the highly significant difference in height at planting, use of this variable as a covariate had little effect and so unadjusted means are presented.

In both experiments there were significant differences between treatments 6 years after planting for height growth, height increment between years 3 and 6 and survival percentage at 3 years ($p < 0.001$ for height and height increment at both sites; $p < 0.05$ and < 0.01 for survival at Craigellachie and Glentress respectively). The differences in 6-year height generally reflect those found at planting (Table 4.4). There was significant variation in form factor between treatments ($p < 0.01$ and < 0.001 respectively).

At Craigellachie, the first cycle cuttings (492/1) were the tallest treatment with the seedlings (492/S) being the smallest and some 40 cm less in height. Second and third cycle cuttings were significantly smaller than the first cycle ones and the third cycle were smaller than the second. However, the only difference in height increment was that the first and second cycle cuttings grew significantly more than the other treatments. Survival was very high with only that of the third cycle cuttings and 2-year-old transplants being less than 98%. The lowest form factor was in seedlings and the highest in the 3-year-old transplants and the second cycle cuttings.

Growth at Glentress was better than at Craigellachie. The first cycle cuttings were again the tallest treatment but here the third cycle cuttings were the smallest. The third cycle cuttings were again significantly poorer than the second cycle ones with the seedlings being intermediate between the two. The same general trends were found for height increment. Survival of the seedlings was lower than that of the other treatments. The third cycle cuttings had a higher form factor than all other treatments except the 2-year-old transplants. Seedlings again showed the lowest form factor.

Table 4.4 3-year survival, 6-year height growth and form factor of seedlings, transplants and three different cycles of Sitka spruce cuttings

Craigellachie

	492/S	*492/1*	*492/2*	*492/3*	*1+1*	*1½+1½*	*5% LSD*
Planting height (cm)	11.9	28.1	25.4	20.0	17.6	37.6	1.7
Survival (%) year 3	100	98.8	100	97.5	97.5	100	2.0
6-year height (cm)	135.1	173.9	160.1	145.5	144.2	146.4	12.9
Height increment years 3–6 (cm)	85.4	104.7	97.6	86.7	88.3	82.0	9.2
Form factor	0.54	0.56	0.59	0.58	0.57	0.59	0.03

Glentress

	492/S	*492/1*	*492/2*	*492/3*	*1+1*	*1½+1½*	*5% LSD*
Planting height (cm)	17.5	27.1	24.7	16.0	20.1	45.8	2.1
Survival (%) year 3	87.7	100	98.8	97.6	100	100	6.2
6-year height (cm)	207.8	239.3	211.8	182.9	188.8	219.4	15.3
Height increment years 3–6 (cm)	137.1	148.5	134.7	119.0	118.5	124.5	10.3
Form factor	0.56	0.57	0.58	0.61	0.59	0.56	0.02

Treatment codes are: 492/S – 1-year-old seedlings of 71(4920P); 492/1, 492/2, 492/3 – first, second and third cycle cuttings of 71(4920P), 1+1, 1½+1½ – 2 and 3-year-old transplants.

Experiments 8 and 9. Tip and base cuttings

Survival figures were very high in both experiments and these data have not been analysed because of the obvious lack of difference between the treatments. No significant differences were found at Speymouth for any parameter although the cuttings grew more vigorously there than at Glentress (Table 4.5).

There were highly significant differences ($p < 0.001$) between families at Glentress for both height and height increment with family 492 cuttings being taller than 980 ones. There were also significant family by position interactions for both parameters ($p < 0.05$ in both cases), largely due to the greater growth of base cuttings of family 492. Cuttings from family 492 were significantly more upright than those from family 980 ($p < 0.001$). A family by position interaction occurred ($p < 0.05$) because 980 base cuttings were noticeably less orthotropic.

Discussion

Any forester purchasing Sitka spruce cuttings must decide whether to plant a pure crop of cuttings or to plant these in mixture with unimproved stock. The former option is frequently favoured as being easier to manage on the ground (c.f. Kleinschmit, 1992), but is probably not financially optimal because some expensive plants are removed as thinnings (Mason and Harper, 1987). Extrapolating from experiment 1, cuttings propagated from families selected for superior vigour should dominate ordinary QCI transplants when both are planted in mixture. The results showed no evidence that pattern of mixing affected the competitive process, so line mixtures which are easier to manage could be used. The 50% superiority in height of the QCI plants was more than would have been expected, since the height differences between pure plots of these origins in nearby provenance experiments was 10–20% at 10 years (Lines, 1987). The latter differences are broadly equivalent to those reported for current commercial batches of cuttings. However, drawing a parallel between provenance mixtures and mixtures of improved cuttings with transplants may not be appropriate since differential provenance growth will be primarily a function of climatic matching (e.g. shorter growing season of Alaskan origins).

A major concern of those who use cuttings is

Table 4.5 Survival, height growth and form after 3 years of tip (T) and base (B) cuttings of two half-sibling families (492, 980) on two different sites

Speymouth	*Family*				
	980		*492*		
Position	*T*	*B*	*T*	*B*	*5% LSD*
Survival (%)	100	98.3	98.3	100	n/a
Height (cm)	112.6	108.6	115.2	115.5	9.7
Height increment (cm)	82.4	78.7	81.7	76.8	10.1
Form	2.3	2.5	2.1	2.0	0.6
Glentress	*Family*				
	980		*492*		
Position	*T*	*B*	*T*	*B*	*5% LSD*
Survival (%)	100	100	100	100	n/a
Height (cm)	85.3	82.2	92.5	101.5	7.0
Height increment (cm)	55.6	50.8	58.9	64.1	5.8
Form	1.2	1.5	1.2	1.1	0.2

Note: n/a – not analysed.

that this new type of planting stock should develop normally in the forest. Mason (1991) reported no difference between cuttings and transplants of the same origin of Sitka spruce for height and diameter growth after 10 years in three separate experiments. Generally superior performance of Norway spruce cuttings after 8 years was reported in 16 trials in Sweden (Gemmel and Örlander, 1989). The 10-year results from experiments 2 and 3 offer further reassurance in this respect. At Craigellachie (experiment 2) there were no significant differences between cuttings and transplants of the same origin after 10 years. At Strathyre (experiment 3), the two batches of cuttings from an improved family were about 10% better in height than the average of the QCI transplants and cuttings treatments. The more difficult establishment conditions on this site caused by grass regrowth on old ploughing resulted in generally lower survival than in experiment 2, particularly for the poor quality QCI cuttings. This emphasises that stock quality and/or quality of cultivation can be an important feature in achieving adequate establishment of cuttings. In both experiments, initial differences in stem form had disappeared by 3 years after planting. In both experiments the diameter growth of the cuttings was as good as or better than that of the transplants which is a good augur for long-term volume production. These results with Sitka spruce differ from those with cuttings of radiata pine (*Pinus radiata* D. Don) where West (1984) found that diameter growth could be less than that of seedlings, even though height growth was similar.

As a result of increasing interest in the potential of containerised cuttings (Mason, 1991), the main interest in experiments 4 and 5 lies in the performance of the containerised treatment P2. Growth and survival of this treatment differed between the two sites. At Speyside (experiment 4) on a cultivated and weed-free site, growth and survival were excellent, surpassing the remaining bare-root treatments. However, on a weedier, uncultivated site at Corris (experiment 5), the performance was less good. This stresses that use of containerised cuttings may not be fully effective unless combined with more intensive establishment techniques. The performance of the standard transplant stock is generally poorer than that of the various batches of improved cuttings, although such early differences can only be indicative.

The results of experiments 6 and 7 indicate that performance of cuttings can be affected by propagation cycle and, by extrapolation, by loss of vigour with greater chronological age from seed. Thus, first cycle cuttings generally grew better than second and third cycle cuttings and second cycle cuttings were better than third cycle ones. These trends are clearer for height growth than they are for form factor. This finding is of potential importance since it suggests that genetic gains in volume increment may be eroded by maturation. For instance, the results of experiments 2 and 3, plus most of those reported by Mason (1991), are derived from first cycle cuttings. St Clair, Kleinschmit and Svolba (1985) showed some decline in height growth of clonal cuttings of Norway spruce (*Picea abies* (Karst.) L.) from cycles 2 to 4. A partial recovery in the fifth cycle may have been due to progressive elimination of slower growing clones. Foster *et al.* (1989) report no influence of two propagation cycles (second and third) upon growth of 10 clones of Norway spruce for up to 6 years. However, the ranking of the clones changed between cycles. In our study all cuttings were half-siblings but the clonal stucture was unknown so it is not possible to be sure if there has been any interaction between clones and propagation cycle. Nevertheless, differences after 6 years appear to reflect size differences at planting (Table 4.4). This suggests that the cycle effect, if real, occurs during propagation and its immediate aftermath. Other results (e.g. Kleinschmit, 1973; Mason and Keenleyside, 1988) have shown that it is possible to affect the rooting of cuttings from different cycles by manipulating the fertiliser regime of the mother plants. It is not clear whether this can also compensate for the apparent decline in vigour over cycles reported here.

Experiments 8 and 9 show no difference in forest performance between tip and base cuttings from two separate families. The major differences occurred between the two families with the variation in stem form highlighting the extent to which such characters are under genetic control rather than being directly induced by propagation systems. This indicates that base cuttings can be used as forest planting stock provided the rooted plants are acceptable form. Sometimes base cuttings produce multiple leadered plants (e.g. Blackwood, 1989) if two buds develop competing shoots and such plants should be culled out before planting.

Conclusions and recommendations

Taken as a whole, these results provide a strong indication that Sitka spruce cuttings produced by current propagation techniques (i.e. both tip and base cuttings) will develop normally in plantations and so realise potential genetic gains. The only concern revealed by these results is whether potential gains may be affected by maturation as the chronological age of the source plant increases. However, there is reason to believe that correct manipulation of the source plant can have compensatory effects, at least in the initial propagation cycles. A further difficulty is that all the results in this paper are based upon comparatively young experiments and there is no information given upon the post-planting root development of cuttings. Other studies have considered these aspects. Baldwin and Mason (1986) reported that a plot of Sitka spruce cuttings planted in 1953 had grown as well as transplant controls for 30 years. Mason, Mannaro and White (1986) showed no difference between root development of cuttings and transplants 3 years after planting and the same trend was apparent after 6 years (unpublished data). Eldridge and Spencer (1988) cite Brown (1974) as finding no difference between seedling and cutting root systems of radiata pine 3 years after planting. Perhaps the only area where information is clearly lacking in Sitka spruce is upon the comparative timber quality of cuttings and transplants (Thompson, 1992). However, in radiata pine, Cown (1988) concluded that there should be no loss of timber quality with use of cuttings provided that these were propagated from juvenile parents and that the parents had been proven to have good wood properties. In fact the use of cuttings combined with selection of appropriate genotypes could result in significant increase in the proportion of a log converted for its timber.

Therefore, the general conclusion must be that managers who plant improved Sitka spruce cuttings can expect to increase the productivity of their forests. The provisional guidelines provided by Mason and Harper (1987) can be restated as the following set of silvicultural recommendations.

1. Cuttings should be planted at normal spacing (2 m × 2 m or 2500 plants per hectare) on sites of low Windthrow Hazard Class. The precaution over spacing is necessary until cuttings of improved wood properties are available.
2. First or second propagation cycle cuttings should be preferred until there is clearer evidence that later cycles do not involve some loss in vigour. Both tip and base cuttings make acceptable planting stock provided they have a single leading shoot.
3. Cuttings may either be planted pure or in approximately 3 : 1 mixture with unimproved stock as recommended by Mason and Harper (1987). If the second option is chosen, then line mixtures will be easier to manage on the ground than more intimate mixes.
4. Either containerised or bare-root cuttings may be used. However, the smaller size and lesser root collar diameter of containerised plots means that the former will require more intensive site preparation, weeding and protection for satisfactory establishment, especially when used for restocking.
5. Cuttings should be subject to the same standards of plant quality control as transplants. Poor quality plants should be rigorously culled. The only exception should be for stem form where cuttings typically have more sinuous stems at time of planting but this difference should rapidly disappear.
6. Cuttings should be handled, planted and managed with the care and attention appropriate to valuable high-yielding material. However, in all other respects stands of Sitka spruce cuttings can be managed with the general silvicultural practices appropriate to a particular forest site.

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Paper 5

Growth of Sitka spruce and timber quality

D.A. Thompson, Harvesting and Marketing Division, Forestry Commission, 231 Corstorphine Road, Edinburgh, EH12 7AT, UK.

Abstract

This paper discusses the properties of Sitka spruce in respect of its use in the UK for pulping and paper manufacture, wood based panelboard manufacture and as sawn timber. Special emphasis is given to its use as structural timber. The importance of knots and juvenile wood are singled out as the two features on which silvicultural and genetic attention should be focused. Published work on spruce suggests that vegetatively propagated trees may have the benefit of reduced variability in wood properties, but have the same problems of juvenile wood and sensitivity of density to growth rate that occurs in trees of seedling origin.

Introduction

'Should we grow trees to meet anticipated market needs or should we grow what is biologically best suited to the site and rely on technology to find a way to use the material produced?' (Johnson, 1986). This frequently posed question ignores the parallel development taking place on understanding how to 'improve' trees and their timber and wood properties important for many different uses. Although *per capita* consumption of wood and wood products has risen in line with general economic growth in the UK, sawnwood consumption is more or less static now but can be demonstrated to have fallen over the last 100 years. A coincident increase in wood consumed by processing industries other than sawing during this period confirms that there has been a rise in technological development.

Increased volumes used in wood processing industries cannot be divorced from sawmilling completely because low conversion rates in sawmills (50–60% roundwood to sawnwood) means they provide a significant resource of woody material. The close relationship between sawing and wood processing industries is an important development and not to be overlooked when examining the properties of any timber.

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is grown in Great Britain because it thrives on a majority of those sites available for afforestation. Most silvicultural and genetic research has been devoted to maximising its rate of growth. Rotations can be less than 40 years where wind hazard is severe and soils are fertile. Sawyers and wood processors are concerned that the resource on which their investments depend is changing in its quality in respect to market needs. At the same time foresters wish to know how far preferred qualities can be improved, at what cost and whether they will see a corresponding benefit when the trees are sold.

This question is not new. Pruning Scots pine in Great Britain has long been recognised and advocated as a means to 'improve' timber quality. Unfortunately, the structure of the British sawmilling industry and market for sawlogs has prevented any notable reward for pruning reaching the forester. Lack of confidence in a reward for silvicultural and harvesting techniques directed at improving sawlog quality is still prevalent. To a large measure activities to improve quality are merely slight modifications to techniques already planned. For example, planting at closer spacings is marginally more expensive, selecting crooked trees rather than straight ones when thinning adds little extra cost but improves average tree size at final felling. This paper examines those elements of quality which relate to utilisation of Sitka spruce and considers more fully those aspects where research into quality has been pursued in the UK.

Pulp, paper and wood-based panelboards

The strengths of pulps depend on the morphological, physical and chemical characters of the raw material and on changes to these characteristics occurring in various pulping processes and any subsequent beating process. Of these characteristics, fibre length and wall thickness, the fragmentation or weakening of fibres and microfibrils, the degree of polymerisation of the cellulose, are among the most important (Rydholm, 1965). Damage to fibres and microfibrils and degree of polymerisation of cellulose are determined largely by processing technology. Fibre length and wall thickness are measurable wood properties. Many correlate reasonably well with specific density.

Rydholm (1965) confirms that conifers, including Sitka spruce, are preferred for their long fibres. Elliott (1960) described the variation in fibre lengths within a single tree of Sitka spruce grown in Wales. He reported a range from 1.01 mm to 4.45 mm which depended on position within the tree. Such variation is typical for a large number of parameters describing wood properties. Frequently variation within a tree is greater than variation in means between trees for the same parameter (e.g. Harvald, 1990).

Juvenile wood (Rendle, 1958) and compression wood, which are often associated (Brazier, 1985), are known to exhibit shorter fibre lengths. Juvenile wood has yet to be precisely defined, but is generally considered to extend between 12 to 18 annual rings out from the pith at breast height. Clearly, fast growing plantations will yield considerable proportions of short fibres, especially, if harvested early. The density of fibre walls is consistently around 1.5 g cc^{-1} (Stone, Scallon and Aberson, 1966) so that it is the thickness of fibre walls in relation to lumen diameter and the proportions of early and late wood which determine wood density. Rapid growth increases the proportion of early wood with large cell lumens (Brazier, 1970).

The pulping and paper industries in UK have found British-grown Sitka spruce an attractive wood for their processes not least because it is a clean white wood which minimises the need for environmentally unacceptable bleaching processes.

Wood-based panelboards can be plywoods, flake or wafer boards, particleboards or fibreboards. Defect free timber is a main requirement for plywood but there is no softwood plywood manufacturing in the UK. The overriding feature of quality for panelboards is the glue/wood bond strength and its water resistance. Wood quality is less important for nonstructural boards and all UK processors accept Sitka spruce except for the manufacture of a structural grade oriented strandboard (OSB) which requires a major proportion of pine to retain its strength at specification.

Sawnwood

There are innumerable uses for Sitka spruce sawnwood which is generally liked for its clean white appearance, ease of nailing and generally small knots. A number of British Standards describe the quality of sawnwood required for specific uses. These divide between those for structural uses and others. Grading sawn timber, with the exception of machine graded structural timber, depends solely on visual assessment. Knots, grain angle and growth rate are important and their values for representative grades in a number of Standards are given in Table 5.1. The Standards have great similarity whether for structural use or otherwise. Defects such as rots, stains, resin pockets and insect boreholes are recognised along with drying distortions, twist, bow, spring and cup. Sitka spruce in the UK has been found particularly susceptible to twist and this is seen as being associated with the presence of large amounts of juvenile wood (Brazier, 1985).

Machine stress grading for structural timber has helped British-grown Sitka spruce become

Table 5.1 Examples of grade rules from British Standards

Standard:	*BS 1186: Part 1: 1986*	*BS 1297: 1987*	*BS 1722: Part 5: 1986*
Title:	*Timber for and workmanship in joinery* ***Part 1:*** *Specification for timber*	*Tongued and grooved softwood flooring*	*Fences* ***Part 5:*** *Specification for close boarded fences*
Knots			
a. Surface diameter	Between 1/2 and 1/3 width	Combined diameters: <2/3 width	Between 1/2 and 1/3 width
b. Margin knot area ratio (MKAR)	–	–	–
Total knot area ratio (TKAR)	–	–	–
Slope of grain	1 in 10	1 in 6	1 in 6
Average rate of growth (ring width)	not less than 6 growth rings per 25mm	not less than 4 growth rings per 25 mm	growth ring width <10mm

Standard:	*BS 4978: 1988*	*BS 1990: Part 1: 1984*
Title:	*Softwood grades for structural use*	*Wood poles for overhead power and telecommunication lines* ***Part 1:*** *Specification for softwood poles*
Knots		
a. Surface diameter	–	Sum of diameters: <1/5 diameter
b. Margin knot area ratio (MKAR)	≤1/2 MKAR and ≤1/2 TKAR or	–
Total knot area ratio (TKAR)	>1/2 MKAR ≤1/3 TKAR	–
Slope of grain	1 in 6	–
Average rate of growth (ring width)	growth ring width <10mm	

accepted in Great Britain's sawnwood market. A greater proportion passed this objective criterion than previously passed with visual rules for stress grading softwoods. British Standard 4978:1988 provides rules for meeting the strength classes defined in the British Standard covering *Structural use of timber* (BS 5268: Part 2). The strength classes provide a means by which specifiers can ignore species and concentrate on strength properties only. Strength class 3 (SC3) is a general grade for a wide range of uses while some special uses such as trussed rafters require SC5 timber. Acceptable proportions of Sitka spruce can generally be graded to SC3; in some cases adequate out-turns of SC4 can be obtained but it is unlikely that SC5 will be attempted by sawmillers because out-turns will be too low to be financially rewarding.

Machine stress grading is based on the relationship between ultimate bending strength (MOR) and stiffness (MOE). However both properties are important in construction and the strength class system sets limits for both along with a number of other important attributes. In 1992 European Standards for Construction will become effective; structural timber strength classes will be defined in terms of MOR, MOE and wood density.

The within tree variability referred to earlier includes MOR and MOE. The relationship between these two is not as precise as to be ideal for engineering purposes. Two consequences follow. First, a large safety margin is required in setting limits for structural use. Second, those factors which may be considered important in influencing their values are difficult to assess. There must be a relationship between individual basic wood properties such as density, fibre length, wall thickness, microfibril angles, MOR and MOE for clear wood and the MOR and MOE of large battens. Clearly that relationship is confounded by the effect of knots and grain angle in the sawn piece. Increasingly engineers are unhappy to use data from clear wood as a basis for calculating structural performance. This is one reason for acceptance of machine stress grading which tests the whole batten. However, the complex relationship between the various properties leads to broad specifications for better quality which are not far removed from those derived empirically.

At the Building Research Station investigations have demonstrated that there are thresholds to the importance of knots and density in their influence on stiffness values for British-grown Sitka spruce (BRE/FC internal reports). This work, which is part of the Forestry Commission Research Division's commissioned project on 'The effects of management practices on the quality of Sitka spruce timber', may provide objective criteria for foresters and bridge the gap between studies on wood properties and those which have described the effects of management practices on machine stress grading yields.

Brazier (1986) reported one series of investigations into the effect of tree spacing on log quality, juvenile wood and knots. Knots are important in virtually all grading rules. Although selection through breeeding programmes is important, the space between trees plays the major role in determining knot size and frequency. It is self evident that as stands are thinned and crown depth increases so knot size increases in the upper part of any stem. Equally it is evident that the gap between knots is wider with distance from the pith so that sawnwood from close to the bark in butt logs is less likely to be down-graded because knots are large or frequent. In fast grown Sitka spruce these knots are most likely to be dead knots because branches, even though dead, remain on the trees. Higher up the stem live knots are more likely, which although larger may be more acceptable. The presence of knots, and their size, is important in grading non-structural grades of sawnwood.

For structural timber, the presence of juvenile wood and knots is seen by many authors as a critical feature in fast grown plantation conifers (Flight, Briggs and Fahey, 1990; Senft, 1986). Sawing patterns ensure that it is almost inevitable that construction sawnwood is taken from the centre of sawlogs so that it is impossible to avoid the juvenile wood. Typically in UK, softwood sawmills are restricted to maximum log diameters of 60 cm. There is concern that the relationship between MOR and MOE is changing in Sitka spruce crops felled now and in the future from that found in the slower grown crops which were the source of material originally used to establish the standards for machine stress grading. The same problem has been noted for Norway spruce in Norway (Lackner, 1990).

There is conflicting evidence on how this relationship changes with increasing amounts of juvenile wood. Kretschmann (1990) suggests that MOE is affected but not MOR, however, Chui and Smith (1990) suggest that the reverse is the case for white spruce in eastern Canada. All reports agree that the overall out-turn of acceptable grades of sawnwood are reduced. Compression wood in Sitka spruce has been shown to reduce MOE but perhaps not MOR (Dhubhain, Evertson and Gardiner, 1988). The same study suggested that one effect of compression wood may be to increase the likelihood of brash failure, which has serious implications in respect of impact loading resistance.

Although there are a great many timber and wood properties that have not been mentioned above, there is currently a concensus of opinion that the two most important features of softwood plantation trees which determine sawnwood properties are knots, for all grades, and juvenile wood for structural timber grades in particular. Silviculturally, the single most effective treatment is to grow trees close together particularly during the early part of a rotation. The wide variation in properties between and within trees suggests there is great potential for genetic improvement. Increased vigour does not automatically imply lower wood density although most data sets show an inverse relationship. However, an overall increase in wood density is not particularly important; improved fibre length and density in the juvenile wood only are the main prerequisites for improving quality.

Just as the penalty for growing trees close together to reduce knot sizes is probably reduced volume for individual trees, so there is likely to be a penalty for changing the properties of the juvenile wood. There is a need to understand why Sitka spruce in the UK has juvenile wood and compression wood. I believe these to be features of advantage for trees growing in windy climates where stem breakage is a possibility. It has been noted how frequently leaders of Sitka spruce have been broken in thicket and pole stages. Reduced stiffness of the stem in the crown area must be an advantage in strong winds and the less elastic wood of the first year may be a disadvantage. We need to have care that in breeding and selecting trees for stiffer juvenile core wood, we do not open the door on other equally serious problems.

Timber quality and vegetative propagation

More and more stands of trees originating as a result of vegetative propagation will reach sizes which permit rigorous evaluation of timber properties. In the meantime there is relatively little evidence on which to base predictions. Spencer (1987) indicated that vegetatively propagated radiata pine gave practical benefits, in the form of higher yields of peeler logs and better sawnwood recovery. Improvements in Kraft pulp yields from eucalyptus were reported by Campinhos and Claudio-da-Silva (1990) at Aracruz, Brazil and elsewhere. Those properties important to pulp quality, namely basic density and fibres per gram of pulp, are being used in the selection of eucalyptus clones.

The wood properties of spruces are distinctively different from those of radiata pine and eucalyptus. Olesen (1982) has studied vegetatively propagated Norway spruce in Denmark. He suggests that the strong influence of ring width on basic density confounds any general trend for wood from cuttings to be of lower density than that from seedlings. This does not conflict with the findings of Nicholls, Pawsey and Brown (1976) and Sweet and Harris (1976) and reaffirmed by Cown (1988) for radiata pine, it merely emphasises the significance of environmental influence on spruce properties when grown in north-west Europe. Olesen (1982) reported changes in tracheid width and basic density which may result from cyclophysis. He made inferences about the influences on wood formation of the maturity of the apical meristem and the process of ageing for the cambium. It is apparent that juvenile wood cannot be avoided in cuttings because this results from the latter process. Olesen's results suggest that one immediate benefit from vegetatively propagated trees will be reduced variability in wood properties. As indicated earlier, the variability in properties of timber is one of its major disadvantages as an engineering material. There is good evidence that one of the effects of a mature apical meristem is to enhance uniformity in timber.

Conclusions

As a result of deliberate Government Policy, UK now has thriving forestry, wood processing and sawmilling industries. Market demands in UK are largely satisfied by imports but for British forestry to remain viable the highest returns must be achieved within the limits set by the properties of the wood resources. As the commonest softwood planted, the properties of Sitka spruce grown in the UK are paramount to the performance of the whole industry. It is generally satisfactory for the pulp and paper industries and acceptable for most of the panelboard industry. The most financially rewarding outlet for growers is sawmilling. Sitka spruce sawnwood has many acceptable features which make it suitable for a wide range of uses but these tend to be at the lower end of the market. Reductions in the size and frequency of knots would increase its acceptability in non-structural markets where appearance is important. These may also lead to improved performance as stress graded timber for structural use. A reduction in the size of the juvenile wood core or improvement in its properties would improve the proportion of sawn battens classified in strength classes suitable for structural use.

In reaching for these improvements in the short term, foresters must face up to more expensive establishment and maintenance and longer rotations before improved strains or clones of genetically better potential timber are commonplace. It is very likely that processing technology will provide faster solutions; for example structural laminates are already the subject of much investment. Such developments are unlikely to change what should be the objective of foresters because sawmillers will continue to pay premiums for good quality timbers while timber processors will always seek to use relatively cheap and abundant raw material.

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Paper 6

Likely increases in volume and revenue from planting genetically improved Sitka spruce

***S.J. Lee**, Tree Improvement Branch, Forestry Commission, Northern Research Station, Roslin, Midlothian, EH25 9SY, UK.*

Abstract

Unless progeny tests are designed to yield meaningful results over a full rotation, likely final rotation gains from improved production populations have to be based on extrapolation of data from juvenile tests. The oldest data collected to date in a Sitka spruce wind-pollinated progeny test were 27-year volume, height and diameter. The predicted increase in final rotation volume of currently available improved Sitka spruce planting stock is estimated at 15% which is approximately equivalent to one full Yield Class. Data are supplied to show the increase in revenue attributable to the use of the genetically improved planting stock. Potential gains are expected to rise to 25% by the end of the century. Increases in revenue due to genetic gain for stem form and wood quality will be positive but cannot yet be quantified.

Introduction

As genetically improved Sitka spruce planting stock becomes available, forest managers require information on genetic superiority and increase in revenue compared with unimproved stock.

Ideally, comparisons would combine the end-of-rotation gains achieved in all selected traits such as volume, straightness, branching characteristics and wood quality measured in stands of trees raised from genetically improved seed. Such final crop comparisons are unavailable for Sitka spruce (and indeed, for most other species). In reality predictions have to be calculated which rely on correlations between juvenile and adult stages of development. These relationships may be established from the oldest, well replicated progeny tests although additional problems arise since these genetic tests were established with the objective of estimating the genetic quality of the field selected 'plus trees' rather than predicting final rotation gains from improved planting stock. Different experimental designs are ideally required to optimise each of these objectives.

By extrapolating the oldest reliable progeny test data, applying proven genetic and mensurational principles, and studying the experience of other tree improvement organisations elsewhere in the world, it is possible to make predictions of final rotation gains, particularly for volume. This paper will familiarise the forest manager with the gains currently being predicted as well as the age, amount, quality, restrictions and limitations of data involved.

Plot size and juvenile / mature correlations

It would be frustrating and inefficient for the tree breeder to wait until final rotation before being able to confidently evaluate the best families in a progeny test. Tree breeders are constantly striving to reduce the age at which family performance can be confidently evaluated in order to increase the gain per year and the speed with which generations can be turned over. Decisions to reduce the age of family evaluation are based on correlations between juvenile (pre-onset of inter-tree competition) and mature data.

If correlations are good then the breeder is justified in making decisions at the juvenile age.

Once it has been decided that progeny tests are not required to last beyond the onset of competition, the experimental design can be altered accordingly. For example, large-plot progeny tests are often required to give reliable data beyond the stage of inter-tree competition. If selection of superior families can take place before the onset of inter-tree competition then alternative designs, such as line plots or single tree plots, can be employed requiring fewer trees to assess accurately the performance of each family at each site. The rate of progress of the testing programme will then be increased assuming nursery and field resources are fixed.

The general trend throughout the world has been to evaluate families as young as possible employing progeny tests with 1 to 10 plant line plots. Consequently, final rotation gains of superior families have rarely been measured simply because few progeny tests have been designed to yield results for the necessary period of time. Predictions of gain are made by extrapolating juvenile performance.

Foster (1986), for example, found excellent correlation between 15-year family mean volume and 5-year height in loblolly pine (*Pinus taeda*). Lambeth (1980), working again with *Pinus taeda*, confirmed that if good juvenile/mature correlations exist, early selection of superior families and a shortening of the breeding generation interval is possible.

For Sitka spruce, family mean juvenile/mature correlations of up to $r = 0.87$ have been estimated between 6-year height and 27-year volume, 6-year height and 15-year diameter, and 10-year height with 22-year diameter (Tables 6.1, 6.2 and 6.3; also Gill, 1987 and Lee, 1990). Superior families are now selected for the breeding population (used in future breeding work) and production populations (the best available clones in the breeding population used solely for the production of planting stock) based on height at age 6 or 10 years. The experimental design used by the Forestry Commission is normally eight plant line plots with five complete replications at each of three sites.

Presentation of genetic gains

The superiority of selected families can be expressed as a percentage gain relative to an unimproved seed lot for the same trait and age. Gain is rarely expressed in terms of the growth potential convention (Yield Class or Site Index), since the trees are too young and the low concentration of trees on the ground precludes the calculation of top height. Problems can arise in relating percentage gain back to the growth potential convention which is usually necessary for detailed financial appraisals.

Confusion can also arise in stating the percentage superiority without stating the trait or the age at which the trait was measured. A percentage figure should always be qualified with trait and age. To this end the Tree Improvement Branch has endeavoured always to state gain in terms of percentage superiority for 10-year height.

Observed gains from existing progeny tests

Measured gains from a limited number of selected families have previously been presented in Lee (1990). Some of these data are repeated here or presented in a new format along with previously unpublished data.

1. Kilmichael 1 P53
(Argyll, Scotland)

This was the first Sitka spruce progeny test planted in Britain. It contained just eight fully replicated wind-pollinated families collected from 'plus trees' selected within various forests in Britain. Since the experiment consisted of 10 × 10 plant plots (replicated twice), it does allow the calculation of top height and Yield Class. Volume, height and diameter were all measured after a delayed first thinning at 27 years prior to the trees blowing down. These 27-year data are the oldest data from a Sitka spruce progeny test. Information relating to the best family, the mean of the best six families and the control consisting of unimproved direct import seed from the Queen Charlotte Islands (QCI) are given in Table 6.1. Performance of height against age is presented in Figure 6.1.

This experiment was established on a fertile site. The unimproved QCI control grew at Yield

Table 6.1 Kilmichael 1 P53 – Sitka spruce open-pollinated progeny test

Family	*6-year height*		*10-year height*	*27-year top height*		*27-year volume*	
	m	*% of QCI*	*% of QCI #*	*m*	*% of QCI*	*m³*	*% of QCI*
Best family	2.01	138	127	20.6 (YC 26)**	109	0.175 (YC 20)	125
*Mean of best six families	1.80	123	116	19.8 (YC 24)	105	0.161 (YC 18)	115
QCI control	1.46	100	100	18.9 (YC 22)	100	0.140 (YC 18)	100
Phenotypic correlation with 6-year height***						0.86	

Calculated based on 6-year performance.
* Families which exceeded the QCI control by 10% at 10-year height.
** From Edwards and Christie (1981) 1.7 m spacing. No thin tables since no thinning prior to this 27-year thinning (first thinning should have been at 18 years).
*** From Gill (1987).

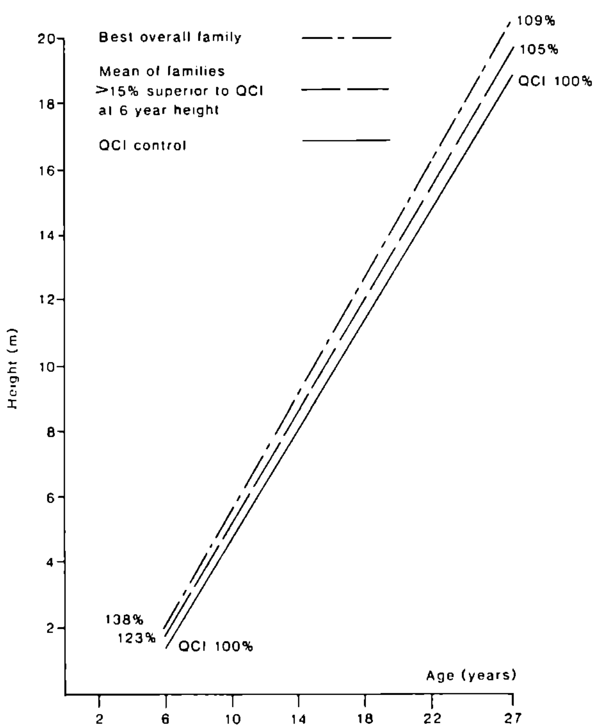

Figure 6.1 Heights of Queen Charlotte Islands (QCI), best individual family and mean of best families, i.e. >15% than QCI, at 6 and 27 years. Height of the latter two genetic material also expressed as a percentage of QCI at these two ages.

Class (YC) 22 and the best family at YC 26 based on top height. If YC tables are examined to investigate volume data, a 14% increase in volume is required at 27 years to be equivalent to an increase in 1 Yield Class when the base growth rate is YC 22; the best families in this progeny test exceed this figure at 27 years.

Volume data from this site were interpreted by Mason and Gill (1986) as meaning that whatever the percentage superiority of the selected families relative to the QCI control for 10-year height, the percentage superiority for volume at close to rotation age would be of an equivalent magnitude. (Ten-year height was not measured in Kilmichael 1, but comparison of 6- and 10-year height data from other experiments allowed calculation of a conversion factor (Lee, 1990).) This clearly involved some approximation but was adopted as a workable convention. Qualification is inevitable as more data become available.

The apparent relationship between 10-year height and later volume lead to the adoption of 10-year height as the standard trait and age for stating genetic gain in the Sitka spruce breeding programme.

Table 6.2 Clones selected in Sitka spruce P67 Series 1* – Aultmore 1 and Whitrope 3 P67

Family	*10-year height*		*10-year diameter*		*22-year diameter*	
	m	*%*	*cm*	*%*	*cm*	*%*
SS 94	5.00	117	7.88	118	16.00	113
SS 120	4.72	110	7.31	109	15.43	109
SS 140	4.85	113	7.67	114	16.20	114
SS 492	4.60	107**	6.95	104	15.02	106
SS 689	4.78	111	7.61	113	16.90	119
Mean	4.79	112	7.49	112	16.00	113
QCI control	4.28	100	6.70	100	14.20	100
Phenotypic correlations:						
10-year height		1.00		0.93		0.76
10-year diameter				1.00		0.87

Notes: *Familes which exceed the QCI control by 10% at 10-year height.
**Included due to excellent form.

2. Aultmore 1 and Whitrope 3 P67 (Series 1 P67)

(Moray, Scotland and Borders, Scotland respectively)

These were the next Sitka spruce progeny tests to be planted after Kilmichael 1 P53. All 50 families were wind-pollinated collections from 'plus trees'. Plot size was just four plant line plots with four replications; top height calculation by family was therefore not possible. Height was last measured at 10 years, after which only diameter has been recorded. The families listed were all selected for the breeding population based on 10-year height (Table 6.2). Family mean correlations of 10-year height and diameter, and 22-year diameter are good although inter-tree competition will be a confounding factor at 22 years. The superiority at 22 years of trees selected at 10 years is still apparent since the mean diameter of the selected families is 13% better than the QCI unimproved control. The degree to which inter-family competition is exaggerating this gain remains unknown.

3. Three series of well replicated progeny tests planted in 1970, 1971 and 1973

(Numerous sites across Scotland, central Wales, north and west England)

Table 6.3 summarises data from each of the three series. Plot size varied by experiment but was usually eight plant lines with five replications. The number of families present in each series is given in Table 6.3. As with the P67 experiments calculation of top height by family was not possible. Diameter at 15 years was the last assessment. No further assessments will be carried out since competition between unrelated families across rows will confound the relative genetic superiority between families.

As in the P67 series, family mean correlations across ages are good. Families that were selected based on 6- or 10-year data retained their superiority at 15 years.

4. Population study – Wark 16 P72

(Northumberland, England)

The objective of this experiment was to investigate the genetic variation within an unimproved stand selected at random in South Stome, north Scotland. It is not a progeny test of exclusively 'plus trees' but contains families collected from trees across all the dominance classes from sub-dominant to 'plus tree'. (Samuel and Johnston, 1979).

This experiment was designed to yield data on the relative performance of families over an entire rotation. Plot size was 6 × 6. The oldest data currently available are for 17-year diameter.

Figure 6.2 gives details of the performance with time of the top five and top ten families out of the 134 wind-pollinated families present. The families were selected based on 10-year height

Table 6.3 Height and diameters from three series of early progeny tests

Percentage superiority of the top 10% open-pollinated families within each series relative to QCI control are shown and correlation of data across traits and ages

1. P70 data: mean values from across seven sites

	Height		*Diameter*	
	6-year *m*	*10-year* *m*	*10-year* *cm*	*15-year* *cm*
QCI control	1.90	4.38	6.63	10.78
	100%	100%	100%	100%
Best five families out of 48	2.19	4.93	7.51	12.30
	116%	113%	113%	114%
Phenotypic correlation with 15-year diameter	0.76	0.78	0.92	-

2. P71 data: mean values from across seven sites

	Height		*Diameter*	
	6-year *m*	*10-year* *m*	*10-year* *cm*	*15-year* *cm*
QCI control	1.74	3.91	6.22	11.14
	100%	100%	100%	100%
Best four families out of 38	2.14	4.68	7.28	12.52
	123%	120%	117%	112%
Phenotypic correlation with 15-year diameter	0.80	0.81	0.95	-

3. P73 data: mean values from across three sites

	Height		*Diameter*	
	5-year *m*	*10-year* *m*	*10-year* *cm*	*15-year* *cm*
QCI control	1.28	4.25	6.55	12.07
	100%	100%	100%	100%
Best five families out of 49	1.63	5.11	8.13	14.34
	127%	120%	124%	119%
Phenotypic correlation with 15-year diameter	0.78	0.80	0.90	-

and are compared with the experiment mean. No unimproved QCI control is present in the experiment but as families were selected from across the dominance range in proportion to the within stand competition, and assuming normal distribution of genetic quality, the family mean can be assumed to be a close equivalent.

Although the percentage superiority of the top five families is decreasing relative to the mean over the years, the absolute difference is increasing. Presently there is no indication that the curves representing the selected superior families will join that for the population mean.

Since this experiment has been intentionally designed to yield later rotation data, it is hoped that confirmation or refinement of the conclusions drawn from 27-year data in Kilmichael 1 P53 will be possible.

Genetic mechanisms

Progeny tests give an indication of the breeding value (genetic quality) of the selected 'plus tree' by measuring the performance of wind-pollinated progeny collected from those selected trees compared with unimproved stock (in this case, unimproved QCI). Measured family performances in such tests however, do not compare directly with the improved material finally derived from production populations for the following reasons.

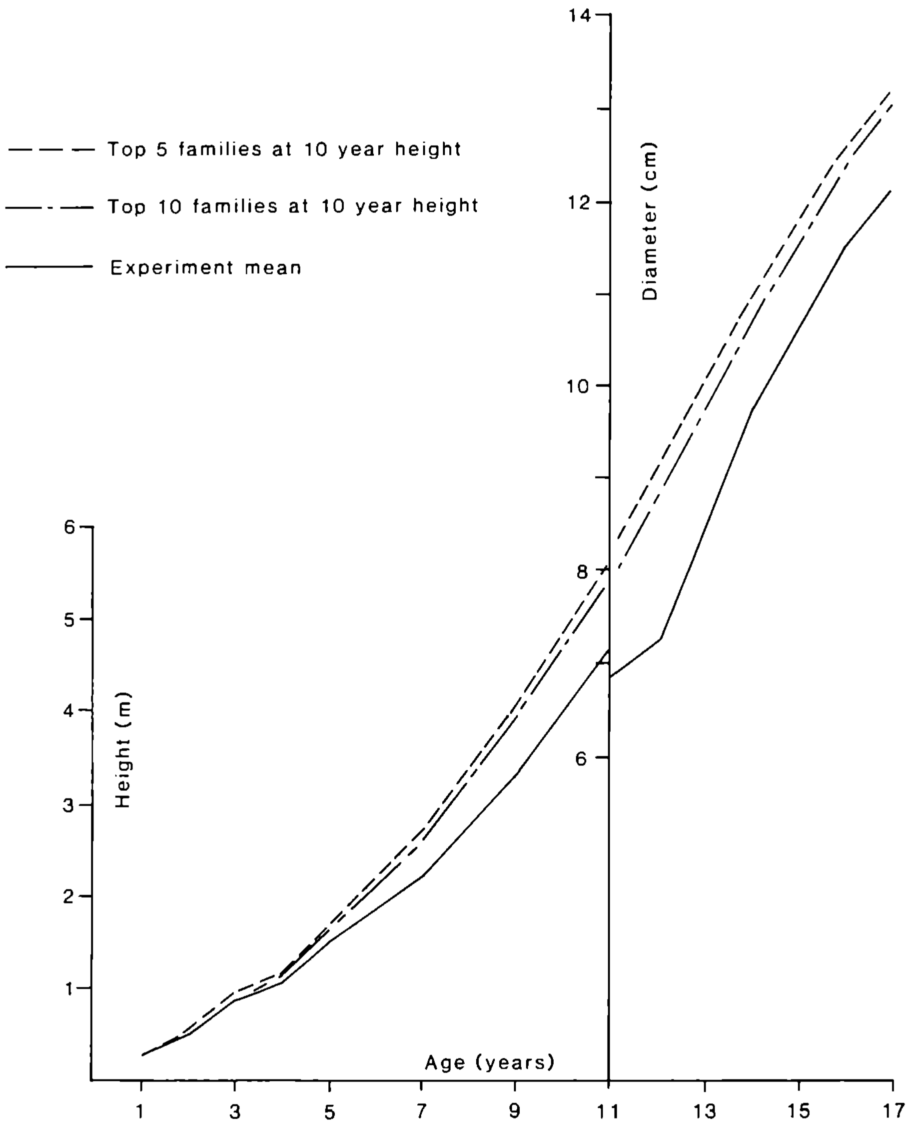

Figure 6.2 Growth in terms of height to age 11 years and diameter breast height from age 11 to 17 years of top 5 and top 10 families as compared to mean of 134 families of the experiment. Families selected on basis of 10-year heights.

1. The pollen source is unknown in wind-pollinated families. It is assumed to have come from a large number of individuals whose average genetic value is equal to the unimproved population mean. Any superiority of families growing in the progeny tests relative to the control is assumed to be solely due to the value of the selected tree. In a tested production population the pollen source is known since the clones which supply that pollen have also been selected based on the superior performance of their wind-pollinated

Table 6.4 Typical family heritability values for Sitka spruce

Trait	*Family heritability†*
15-year diameter at breast height	0.73
17-year stem form	0.65
15-year wood density	0.85

†Calculated from P70 data across seven sites.

families in a progeny test. When both female and male gametes are derived from clones already selected as superior following screening in a progeny test, gains can effectively be doubled (Shelbourne, 1969).

2. Measured family superiority has to be adjusted for family heritability to give an individual's breeding value. Heritability is the degree of confidence a breeder can have that the gain observed in one generation is transferred and expressed in the next. There are various forms of heritability (see Falconer, 1982). Family heritability is the form used to calculate that proportion of gain which can be transferred from the measured superior wind-pollinated family in a progeny test to a production population consisting purely of ramets of the original 'plus trees'. Such heritabilities can vary between 0 and 1 (Zobel and Talbert, 1984); a value of 1 indicates that all the observed gain will be expressed in the next generation while a value of 0 means that none will. Heritability values are peculiar to species, trait, age and site. Typical values for traits within Sitka spruce are given in Table 6.4.
3. Assuming a normal distribution of breeding values, it follows that as the population of clones with calculated breeding values increases with time, the potential genetic gain from successive production populations, which are of a fixed size, will also increase. Effectively, as more clones are tested, the opportunity exists to continually select the very best. Under these circumstances, the 'selection intensity' is said to increase, i.e. the size of the production population decreases as a *proportion* of the breeding population.

Genetic gain of improved planting stock

1. Based on observed breeding values of individual clones

Gains cannot be *realised* until an improved stand is compared with an unimproved stand of the same age and on the same site. Gains which are calculated based on progeny test data are referred to as potential or predicted gains. Potential genetic gains from production populations such as seed orchards and bulked family mixtures (mixtures of seed retaining no family identity derived from controlled pollinations of an elite polymix on tested improved clones) can be calculated by finding the mean progeny performance (relative to the control) of each constituent male clone, adding the mean progeny performance (relative to the control) of each constituent female clone and scaling down the total by family heritability.

Thus: % Genetic gain =

$$\left\{\begin{matrix}\text{Mean progeny performance}\\ \text{of constituent males}\end{matrix} - \text{Control}\right\} + \left\{\begin{matrix}\text{Mean progeny performance}\\ \text{of constituent females}\end{matrix} - \text{Control}\right\} \times \frac{\text{Family heritability}}{\text{Control}} \times 100$$

In a seed orchard the same clones act as males and females and the assumption is usually made that they combine together in equal proportions without any 'selfing'. Potential genetic gain for currently available improved planting stock (early seed orchards and bulked family mixtures) as calculated by this method is 15% for 10-year height. Following Mason and Gill (1986), it is assumed that this will realise a 15% increase in volume at close to rotation age, equivalent to an increase of one full Yield Class based on the experience from Kilmichael 1 P53.

2. Based on genetic components calculated in progeny tests

Genetic gains from production populations can be calculated in a more theoretical way employing the techniques outlined by Shelbourne (1969) using the equation:

$$\text{Genetic gain (G)} = 2i\sigma h^2$$

where i is the 'selection intensity' (proportion saved), σ is the square root of the variance between family means and h^2 is the family heritability (proportion of measured gain passed on to the next generation). The factor 2 is introduced because both male and female parents

Table 6.5 Expected gain from a tested clonal seed orchard based on data collected at 6 and 10 years (height) and 10 and 15 years (diameter)

	6-year height	*10-year height*	*10-year diameter*	*15-year diameter*
1) 40 : 1000	15%	20%	18%	17%
2) 40 : 2000	17%	22%	20%	19%
3) 20 : 2000	19%	25%	22%	21%

have been selected as being genetically superior following progeny testing.

This method does not involve the knowledge of the breeding values of particular clones, rather it is based on calculated heritabilities, between- and within-family variation components and selection intensities corresponding to the proportion of trees selected (Becker, 1964). Such calculations serve as a typical outcome of a selection procedure rather than making the best possible predictions using specific experimental material (Lindgren, Libby and Bondesson, 1989).

Table 6.5 gives the calculated potential gains for 6- and 10-year heights and 10- and 15-year diameter at three different selection intensities based on data derived from the P70, P71 and P73 series. Gain is expressed relative to the progeny mean and ignores the gain of 'plus tree' selection relative to the QCI control. Experience with progeny tests suggests that the gain due to 'plus trees' selection could increase gain by a further 5% for 6-year height decreasing to 4% for 10-year height.

The three different selection intensities given represent:

a. likely gains from early seed orchards – progeny testing programme 50% complete (40 clones selected from 1000);

b. likely gains from late seed orchards – progeny testing programme 100% complete (40 clones selected from 2000);

c. likely gains from a reduced production population – progeny testing programme 100% complete (the very best 20 clones selected from 2000).

Early seed orchards and bulked family mixtures should resemble (a) whereas seed orchards or bulked family mixtures created today should be approaching (b).

Clearly these calculated potential gains are higher than the figures based on the breeding value of the constituent clones. This is possibly due to the fact that the former assumes a normal distribution of clones selected for the production population. In reality this will not be the case since clones which are vigorous but of poor form are actually excluded from the production population. (See 'Form' below.)

It would seem that a 15% genetic gain for height at 10 years and (by deduction) final rotation volume is a conservative but realistic figure for currently available planting stock from seed orchards and bulked family mixtures. Based on volume differences this is equivalent to an increase of one full Yield Class. Limited top height progeny (family) mean data from Kilmichael 1 P53 would seem to confirm this conclusion if all clones used in the production population were of a similar quality to the ones selected here.

This compares favourably with gains in volume reported elsewhere in the world. Carson *et al.* (1990) report realised gains of 15–17% from first generation seed orchards of *Pinus radiata* in New Zealand, rising to potential gains of 30% in volume by combining the very best clones and bulking up the resultant families by vegetative propagation.

Gains for other traits

1. Form

All families that qualify for the breeding population based on height are screened for straightness and branching quality, collectively referred to as form (Figure 6.3), after 7 and 15 years. Only clones with form at least as good as the QCI control are used in the production population. Clones with good vigour but poor form are rejected from the production population,

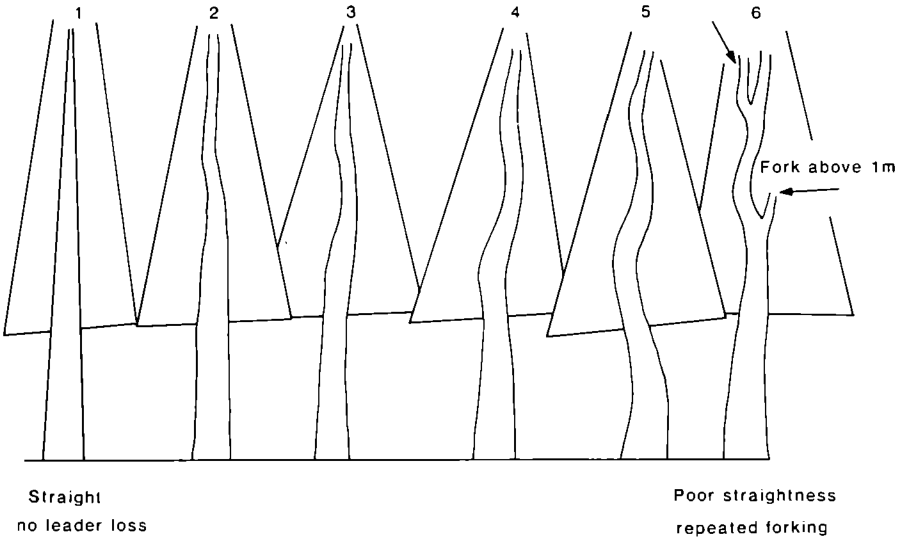

Figure 6.3 Assessment of form based on a scale of 1 to 6.

although they are retained in the breeding population.

The increase in form relative to unimproved QCI of currently available improved planting stock is approximately 7% at 10 years of age (Lee, 1990). It has not yet been possible to put an economic value on this improvement which should result in higher utilisation efficiencies at the sawmill.

2. Wood quality

Wood density has long been considered to be an important factor in the stiffness (strength) of Sitka spruce timber (Brazier, 1967). Wood (1986) found a strong negative correlation (phenotypic correlations amongst family means up to $r = -0.69$) between diameter at breast height and wood density. Clones of good vigour and density can however be identified and included in production populations. Similarly clones of good vigour but well below average density are excluded from production populations.

Families are screened for wood density using a 'Pilodyn' which gives an acceptable, non-destructive assessment by firing a pin into the tree with a given force. Density is inversely related to the distance travelled by the pin. Density using the 'Pilodyn' is not assessed until the trees are 15 years old since that was the earliest age at which Wood (1986) found juvenile wood density to be acceptably correlated $r = 0.65$ at family mean level with mature whole tree density.

Early seed orchards and bulked family mixtures were established before screening for wood density had commenced. It follows, therefore, that the mean density of stands from early production populations is likely to be less than stands derived from direct import QCI.

Recent work by Maun (1989) indicates that branch size and distribution, and straightness of grain are major factors in final timber stiffness and are probably of greater importance than wood density. He has found that if knot surface area is reduced by 10%, then timber density can also fall by as much as 10% before there is an increase in the rejection rate of battens through a machine stress grader.

It is not yet possible to state what effect the tree breeding programme has had on final timber stiffness or even quantify the genetic gain. Since the production population is increased for trees of good form and fine branches it is probable that any decrease in density is more than compensated for by a decrease in knot size and surface area, and improvement in straightness of grain. Work to quantify these separate influences on wood quality continues.

As the breeding programme progresses and the pool of clones available for screening increases, it will be possible to select clones for future production populations with improved density as well as reduced knots and improved form.

Table 6.6 Increase in discounted revenue to year zero in £ per hectare as a result of planting genetically improved trees which increase growth rate by one Yield Class (2 m^3 ha^{-1} yr^{-1})

The figures given indicate the increase in discounted revenue to year zero as a result of planting improved stock on a site that previously grew trees at the Yield Class stated. The increase in discounted revenue in using improved stock on a site which previously would have grown YC16 unimproved Sitka spruce in WHC IV, is £345 ha^{-1} (5% discount rate)

WHC	*MTT/No thin*	*Discount rate*	*Yield Class*				
			12	*14*	*16*	*18*	*20*
					£ per hectare		
I-III	MTT	5%	365	375	385	415	430
		6%	265	295	315	320	315
IV	No thin	5%	300	340	345	365	310
		6%	195	230	270	290	260
V	No thin	5%	210	200	210	200	200
		6%	165	170	175	140	175
VI	No thin	5%	125	110	55	90	45
		6%	105	85	60	85	50

1990/91 prices (Scottish price-size curve for 1989/90 triennium review adjusted for inflation).

Profitability of improved Sitka spruce

Table 6.6. gives the increase in discounted revenue to year 0 (zero) of using planting stock that is 15% improved for 10-year height and 15% improved for final rotation volume. This is assumed to be equivalent to one full Yield Class. The example given is based on typical bare land planting on gleyed soils in the Borders of Scotland and England. A Scottish price-size curve has been used. Slight anomalies in relative increases between yield classes within a Windthrow Hazard Class have been smoothed out by eye.

The assumption has therefore been made that the planting of improved material will result in an increase of one Yield Class regardless of site quality. This assumption has not been fully tested since old progeny tests planted across a range of known site qualities do not exist. Much depends on the performance of improved material compared with unimproved material between the ages of 27 years and final rotation. Investigation of *Yield models for forest management* (Edwards and Christie, 1981) reveals that differences in cumulative volume at age of maximum mean annual increment can vary greatly from 5% between YC 22 and 24 and 17% between YC 12 and 14. The prediction of one full Yield Class across all sites is therefore probably a conservative figure at faster growing sites (in excess of YC 18 with unimproved material) but should just about be attainable at slow growing sites (currently YC 12).

Two discount rates are presented at 5% and 6%. Until recently 5% was the standard discount rate fixed by Treasury for all Government appraisals but this was changed in early 1990 to 6% for all *major* decision making appraisals. The conclusions are similar regardless of the discount rate; only the magnitudes of differences vary.

With the aid of modern computer financial appraisal packages the generation of Table 6.6 is a relatively easy exercise when an increase in genetic gain of one full Yield Class is assumed. Managers can carry out their own appraisals, using local circumstances and price-size curves. Figures calculated may vary slightly from those presented in Table 6.6, however the figures presented here can be used as a general guide.

Managers can decide based on their own circumstances, the premiums that can be paid per hectare for improved planting stock either from tested (approved) clonal seed orchards or vegetatively propagated material from bulked family mixtures (BFMs). If the premium for improved seed or planting stock per hectare is less than the expected increase in revenue on moving from one Yield Class (YC) to the next highest within the relevant Windthrow Hazard Class (WHC), then the use of the improved stock is more than justified. This is the case in all but the highest WHCs. Clearly the benefit of improved stock is greatest on low WHC sites and increases with YC (except in WHC VI) although it seems to peak around YC 18 (increased to 20).

It must be stressed that the increases in revenue stated in Table 6.6 are based on vigour only and therefore likely to be conservative. No account if taken of the likely increases in value due to quality improvements which should upgrade the category of sawlogs and increase utilisation at the sawmill of both thinnings and the final crop. It is also quite possible that the faster early growth rates of genetically improved material may lower expenditure by reducing the number of weedings required to establish a plantation thereby increasing profits further. More conclusive estimates of gain and revenue, including improvements of traits other than vigour can only be made following the felling and comparison at rotation age, of improved and unimproved material.

Likely pathway of genetic gain

Figure 6.4 is adapted (and brought up to date) from Mason and Gill (1986) showing the pathway of *potential* genetic gain and also the pathway of genetic gain of available planting stock. The solid line indicates the calculated gain available from seed orchards or BFMs in the year that they are created; the dotted line indicates the genetic gain by year that the improved stock should be available to the forest manager.

The dotted line lags behind the solid line by the time taken to produce seed and raise the improved planting stock. Since it takes 10-20 years before seedling planting stock becomes available from a newly established seed orchard, yet only 6 years before vegetatively propagated stock is available from BFMs (Mason and Harper, 1987), it follows that a line representing gain solely from seed orchards would lag behind the one presented by a further 4-14 years.

Genetically improved seed from seed stands

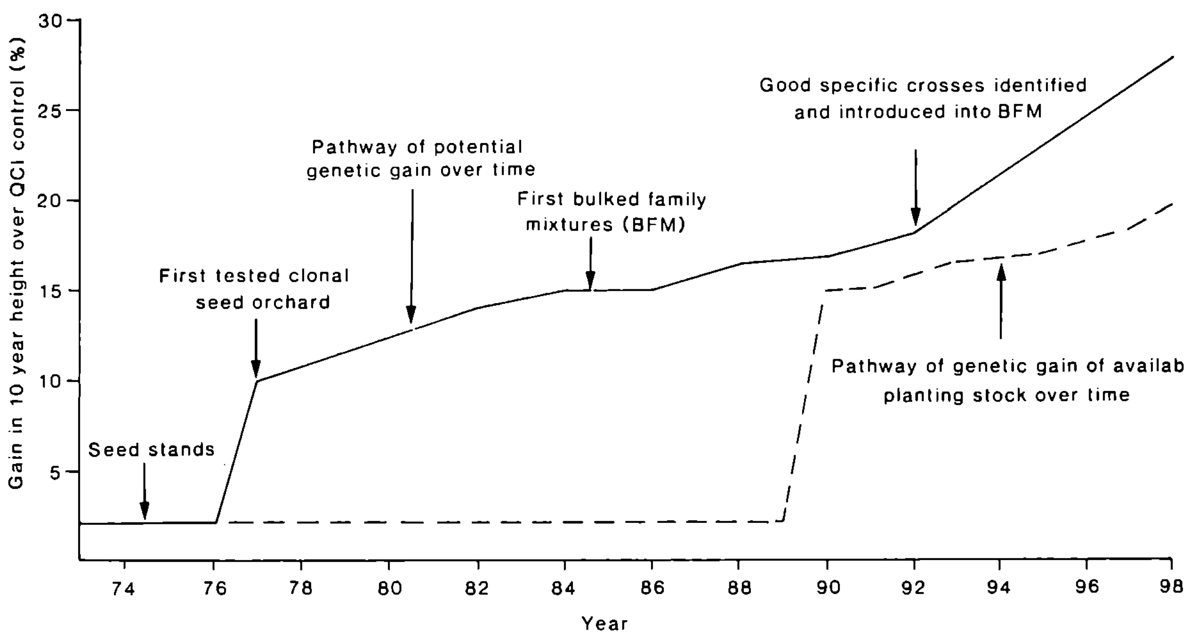

Figure 6.4 Path of likely potential genetic gain and the genetic gain of available planting stock over time from the current tree improvement programme.

gives a 2% gain in final rotation volume over direct import stock from the Queen Charlotte Islands (Gill, 1983) and has been available for over 20 years. The first seed orchard consisting of entirely tested clones was established in 1976 (approximately 10% genetic gain). Orchards were then established approximately every other year; the potential genetic gain increasing with each successive orchard as the selection intensity increased. The first commercial BFM was made available in 1985 (15% genetic gain).

It is expected that by 1992 it should be possible to start introducing into BFMs those families that consist of a single male and female cross and have been identified in the field as performing in excess of the predicted performance based on their individual breeding values. Clones that interact in such an unpredictable and positive manner are said to express good Specific Combining Ability (SCA). Their identification constitutes the second round of genetic testing, which is currently under way. As an increasing number of such families are identified the solid line has the potential of rising to >25% by the end of the century.

Families expressing good SCA can only be recreated by controlled pollination or planting of bi-clonal orchards (orchards containing just two clones). The latter are not a practical proposition due to control of flowering, pollen contamination and cost. It follows that as more families of good SCA are introduced into BFMs (following controlled pollinations) the potential gain from such mixtures will start to exceed that from a seed orchard (dependent on breeding values) established in the same year. The situation will arise by the end of the century that in the same year a BFM is created having a potential gain of >25%, the best possible seed orchard will be established with a potential gain of around 20%. Thus not only will the potential gain from BFMs be realised 4-14 years earlier than that from seed orchards, but the gain from BFMs will exceed the maximum ever attainable from orchards by over 5%.

Retention of genetic gain to final rotation age

Forest managers will naturally be concerned that genetic gain is retained to final rotation age and that there is no change in the internal dynamics of the improved stand. It is currently impossible to answer these questions conclusively since trees of the necessary genetic quality and age do not exist. Data have been presented to show that on one site only, superior families that were identified following 6-year height assessment, were still superior to the unimproved control in terms of 27-year volume (Kilmichael 1 P53). Elsewhere (Population Study), the advantage of superior families shows no sign of decreasing relative to the experiment mean at 17 years of age.

There is no evidence to suggest that the stand dynamics or tree shape should change in improved relative to unimproved stands for a given stage of development. Considerable phenotypic variation for vigour and form will still be retained in the improved stand but on average it will be growing at a higher Yield Class and with improved form.

Buford and Burkhart (1987) found no change in stem taper when comparing plots of trees from 8- to 17-year-old improved and unimproved loblolly pine (*Pinus taeda*). They concluded that the primary relationship that appears to be altered through genetic selection is the height-age curve, i.e. site index (or Yield Class). However, Sprinz, Talbert and Strib (1989), found that site index trends did vary when comparing sources of loblolly pine from the east and west of its distribution. They found that eastern sources grew faster than western until age 25 after which the height of growth of western sources was superior. They concluded that rotation length would be a criticial factor in selection of seed sources if common height levels were to be eventually reached. Data on later rotation performances of families (as opposed to seed sources) are very scarce.

Little further information is gained by studying the performance with age of Sitka spruce, or Scots pine origins, in tests over a number of sites in Britain. Care has to be taken in extrapolating data of relative performance over time from a provenance test to a progeny test. The former is concerned more with adaptability whereas the latter is concerned with economic traits within generally well adapted origins.

Few origin tests are much older than the earliest progeny tests. Comprehensive, well-replicated Sitka spruce origin tests were planted in 1960 and 1961 but the data collected were not always consistent being sometimes top height and other times basal area. In Wales, however, Washington origins (located to the south of QCI) which were identified as having superior height increments relative to QCI at 10 years old were still superior at 20 years, for either basal area or top height (Lee, unpublished data). In Scots pine, comparisons of indigenous (well adapted) provenances over three sites in Scotland found that differences were retained up to 32 years old (Lee, unpublished data).

When selecting within an origin, Cannell (1979) warns tree breeders against the selection of 'competitive' ideotypes (or clones) which capture the site rapidly after establishment but then slow down to the detriment of long-term volume. Selection instead, should be for 'crop' ideotypes which make most efficient use of the site when in competition with other individuals, and distribute most of dry matter about the harvestable stem. The concern is that early selections may only have initial superior growth rates that are not sustained to the end of the rotation. Lee (1987) reported that Sitka spruce clones selected for vigour at 6 years old have narrower crowns per metre of height than less vigorous families. This suggests that if the rate of site occupation is increased by planting genetically improved material, it will be due to more vigorous height growth and not due to any unproportional increase in lateral branch growth.

Clearly large plot competition studies are required to investigate final rotation gains and per hectare productivity further and allow comparison with gains and predictions based on eight tree row plots. Such studies are now in hand. Evidence presented here suggests that clones selected as superior early in the rotation retain that superiority until at least 27 years.

Conclusions

The purpose of this paper has been to make reliable predictions regarding the genetic gain and subsequent profitability of genetically improved Sitka spruce relative to unimproved direct import material from the Queen Charlotte Islands.

Final rotation genetic gains have to be based on the extrapolation of juvenile results. The oldest progeny test data available are 27-year volume, height, and diameter. A 15% genetic gain for final rotation volume is predicted for currently available genetically improved stock. This is equivalent to approximately one full Yield Class at final rotation. The genetic gain for form will be 7%. Gains in wood quality cannot yet be quantified.

The increase in discounted revenue to year zero as a result of planting genetically improved Sitka spruce is positive on all site types considered and varies considerably with Yield Class and Windthrow Hazard Class. The benefit is greater at lower WHCs. Volume gain is expected to increase further in the mid to late 1990s as superior full-sib families are identified; such extra gain will only be available from BFMs.

More studies are required to investigate the internal stand dynamics of the improved material and confirm that the gains predicted are realised at final rotation.

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Nitrogen deficiency in Sitka spruce plantations (FC Bulletin 89; 1990)	£3.00
The green spruce aphid and Sitka spruce provenances in Britain (FC Occasional Paper 19; 1988)	50p
Mechanical characteristics of Sitka spruce (FC Occasional Paper 24; 1989)	£1.50

Research Information Notes (free)

143. Early forest performance of Sitka spruce planting stock raised from cuttings
150. Wind-tree interaction studies in Sitka spruce plantations
154. Tolerance of Sitka spruce roots to waterlogging
164. The nutrition of Sitka spruce on upland restock sites
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