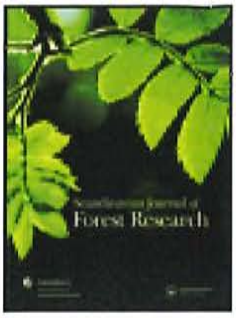

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Comparison of noble fir progeny from US Pacific Northwest collection regions and Denmark for Christmas tree traits

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ABSTRACT

Noble fir is the leading Christmas tree produced in the US Pacific Northwest (PNW). This study is based on evaluations of 24,721 trees collected from five native collection regions in Oregon and Washington plus imported seed from Denmark. The major collection areas were further subdivided into provenances utilizing 16 in the PNW and 6 from Denmark. A total of 22 test sites were evaluated from progeny trials planted between 1996 and 2007. Traits important for commercial Christmas tree production were evaluated and include commercial height, tree grade, value and colour. Tree height and quality were positively correlated while colour showed little correlation with either trait. Provenances from the Oregon Coast and Willapa Hills, Washington provided the highest potential gain for Christmas tree market value. Provenances from Denmark exhibited superior colour and slow growth. For breeding purposes, the gain from backwards selection estimated a range of improvement in marketable value from 0.91 to 1.22 Euros per tree.

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Abies procera; Christmas tree quality; colour; grade; height; value

Introduction

Noble fir (*Abies procera* Rehd.) is the leading Christmas tree species produced in the states of Oregon and Washington (USA) with yearly plantings of over 4.8 million trees (USDA 2014). Bough and greenery harvest levels in the region averaged 7257 metric tons per year. In Denmark, noble fir is primarily utilized for greenery production with an annual harvest of 23,000 metric tons while Christmas tree production is a niche product (Christensen 2015 pers. comm.).

The natural distribution area for noble fir extends from Stevens Pass in Washington (47° 44′ N) along the Cascade mountain range to the vicinity of the McKenzie River (44° N). In the Cascade Range the species naturally occupies middle to high elevation sites (1000–1700m) (Franklin 1990). Noble fir occurs at lower elevations (550–1200 m) along the Coastal Mountains from near Grass Mountain (44° N) to Baw Faw/Bouisfort Peak in the Willapa Hills of SW Washington (46° N) (Figure 1).

Noble fir was identified in 1825 by David Douglas and seeds were collected in 1826. Though the exact location appears vaguely in Douglas' journal, the likely collection site is in the Eagle Creek area N. of Mt. Hood in the Oregon Cascades (Nisbet 2009). Noble fir was introduced into Great Britain in 1831 (Kranenborg 1988). Though not a major species, it has since been widely planted in Europe and in a number of countries, land races and seed stands have developed.

Research relating to the adaptability of the species outside the native range was aided by a 1978 International Union Forest Research Organizations (IUFRO) sponsored seed collection utilizing up to 17 provenance seed collection areas (three sites from Coastal Oregon, six sites from the Washington Cascades, seven sites from the Oregon Cascades with one Danish landrace). The trial was planted in British Columbia (12 sites), Britain (eight sites), Germany (six sites), Ireland and Norway (five sites each), Czech Republic and Denmark (three sites each) and France (two sites). Broadly, the end-use (timber, greenery or Christmas tree) and planting site selection emerged as a critical first step important in seed source selection (Xie & Ying 1994; Lipow et al. 2002; Thompson 2005).

Within native stands in Oregon and Washington, tree seed collection and transfer guidelines primarily focusing on timber production have undergone a number of revisions. The most commonly utilized guide for the purchase and collection of seed, utilizes fixed seed zones established in 1966 (Forest Seed Council 1966). Revised transfer guidelines (Randall 1996; Randall & Berrang 2002) suggest broader species specific transfer zones. These revised guidelines recognize two elongated zones in both Oregon and Washington. The Coastal Zone (from 46° N to 44° N) runs from the Willapa Hills in Washington along the Oregon Coastal mountains. The Cascade Zone (from 48° N to 44° N) runs from the Washington and Oregon Cascades to near Oak Ridge where Shasta fir (*Abies magnifica* var. *shastensis* Lemm.) forms an interfertile species mixture with noble fir (Sorensen et al. 1990).

Efforts to find superior noble fir sources for Christmas trees in the PNW began as the first trees were harvested in the 1960s from wild stands. As production moved into plantations, provenance tests were initiated in the 1970s (Brown 1976). These early tests identified the Mid-Oregon Coast Range (around Polk County), and the S. Washington Cascades

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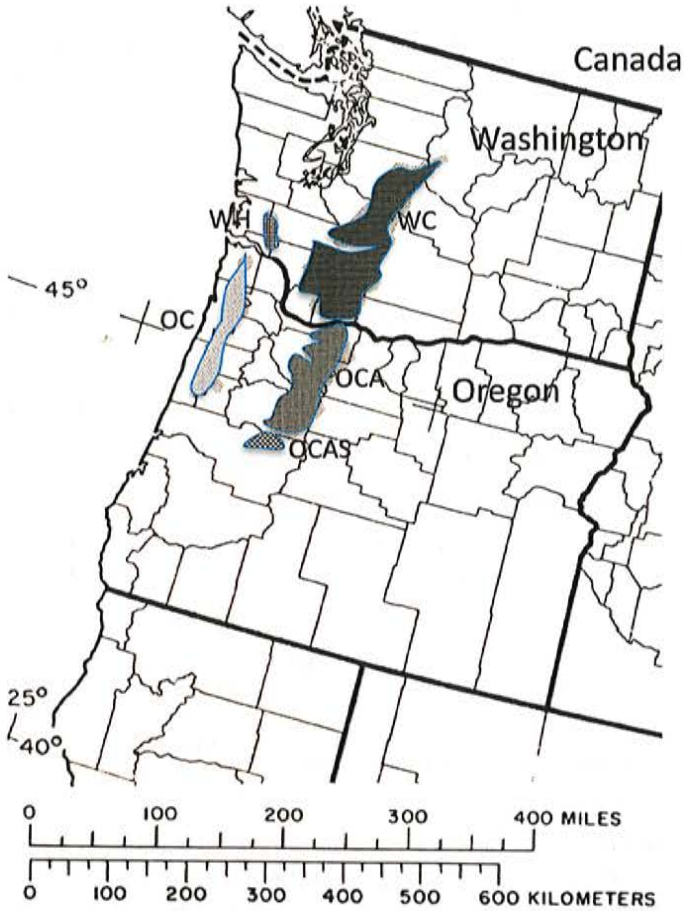

Figure 1. Noble fir distribution and range of sampled seed sources. OC, Oregon Coast; WH, Willapa Hills, Washington; WC, Washington Cascades; OCA, Oregon Cascades Area; OCAS, Oregon Cascades Area South (after Franklin 1990).

(Cowlitz County) as excellent potential seed collection areas. Importantly, the evaluation protocol was based on the PNW production system targeting markets located primarily in the Southwest US (California, Arizona, and New Mexico).

The PNW Christmas tree production system begins with planting 2–3 year-old seedlings at a nominal spacing of 1.7 m between both trees and rows. Fields are kept clear of competing vegetation throughout the rotation period. Rotations lengths to harvest are typically 7–9 years after planting depending on product goals, site and cultural practices. Typical cultural practices include maintaining a single dominant leader and side shearing trees when the taper exceeds 50% relative to tree height. When tree height reaches 1.3 m, the leader is trimmed to 30–40 cm in length yearly to increase tree foliage density. Typical final harvest heights are between 180 and 245 cm. Traits of importance in this production system include rapid early height growth, ample bud and branch density, upright branching, healthy appearance and colour.

In contrast, in the Danish production system noble fir greenery is the primary product. Traits important in this production system are bluish/green colour, upright needles, slower height growth and relatively short dense branches (Nielsen 2007). Initial planting spacing is between 1.2 and 1.5 m. Seedling are typically 3–4 year-old bareroot stock. Trees harvested for Christmas trees will be 7–10 years of age and only 5–20% of the planting will be removed while the remaining stands are utilized for greenery (Jøhnk et al. 2000). The European Christmas tree market favours an open-grown layered tree with minimal top or side trimming. Final tree heights at harvest are typically between 175 and 225 cm. Among provenances of the Danish landrace only minor differences have been seen for Christmas tree quality, when grown unsheared (Jøhnk et al. 2000), but larger single tree differences within seed sources were reported in an early study (Roulund & Jensen 1990). Based on a minor set of seed sources, Danish sources seem slower growing and have a bluer needle colour compared to tested Oregon and Washington sources (Nielsen 2007). Historically, the re-introduction of Danish seed sources to the PNW have been driven by the bluish colour and seed availability in years where natural seed production is scarce in the PNW.

Beginning in 1996, progeny trials were established by Oregon State University Extension Staff that eventually included 230 half-sibling families, 21 full-sibling families and 6 seed stands. The objectives in establishing and evaluating these tests through time are many. Important investigation questions include: (a) are there identifiable areas where one could expect higher value genetic material?; (b) how much genetic gain should be expected for the traits investigated?; (c) what is the genetic variability and heritability of the traits

Table 1. Overview of genetic entries and representation in the series across years.

Provenace/county						No. of seedlings in planting year (No. of test sites)							
Name	Code	Area	No. hs	fs	st	1996 (3)	2000 (3)	2001 (2)	2002 (4)	2004 (4)	2005 (4)	2007 (2)	Area
Lewis	Lewis	WH	6							600			600
Cowlitz	Cowlitz	WCA	10						700	270			
Clark	Clark	WCA	5						400	100			
King	King	WCA	4							400			1870
Tillamook	Tillamook	OC	6				75	164	198		115		
Yamhill	Yamhill	OC	1				75						
Riley/Fanno	Riley/Fanno	OC	16	17		490	965	95	800	300	355	100	
Polk	Polk	OC	26	1		860	75	590	500	275	135	85	
plus-tree	plus-tree	OC	70	3					555	100	4800	1174	
StottMountain	StottMountain	OC	28							2795			
Lincoln	Lincoln	OC	5					244		100	120		
Benton	Benton	OC	18				225	466	100	515			17,446
Clackamas	Clackamas	OCA	8			540	375						
Hood River	Hood_River	OCA	2				150						1065
Seed zone 482–5	482–5	OCAS		1				100					
Lane	Lane	OCAS	21								2275		2375
F587 Ulborg, Fejsø	F587	DK			1				100				
F433 Salten Langsø	F433	DK			1				100				
F432 Det Grønske	F432	DK			1				100				
FP623 C.E.Flensborg (families)	DHF	DK	4			790							
FP623 C.E.Flensborg (bulk)	DH	DK			1	200							
F.710 Langesø	Langeso	DK			1		75						1365
			230	21	6						Total trees	24,721	

Notes: State of Washington: WH: Willapa Hills (coast); WC: Washington Cascades. State of Oregon: OC: Oregon coast; OCA: Oregon Cascades; OCAS: southern part of Oregon Cascades; DK: Danish land races of unknown origin. hs: number of half-sibling families; fs: number of full-sibling families; st: number of stand collections.

in question?; (d) are important traits mutually compatible?; (e) how does the Danish material perform when evaluated in a PNW production system?; (f) how do results from these region-wide collections compare to previous gene ecological zonation studies of noble fir.

Materials and methods

Sites

Test sites were planted over an 11-year period beginning in 1996. All test sites were established on commercial Christmas tree plantations in Oregon or Washington. The number of planted test sites varied from three to seven depending on the planting year, seedling availability and planting success (Table 1). Initial planting spacing varied from 1.5 m to 1.8 m depending on producer preference. A randomized nearly complete block design was used generally comprising 5 blocks per site and 5-tree row plots, although 10-tree row plots was used in trial year 1996. Generally, each genetic entry was represented by one row plot per block.

The test sites were all in the major producing region for noble fir and covered a production range between latitude 44°– 46° N. Each planting was located on sites known for successful noble fir production in the past and each was managed by the producer in conjunction with typical production practices for their farm. Test sites were typically surrounded by noble fir plantings from the same planting year. Each producer at each test site targeted production of 1.8–2.3 m. dense noble fir. More test sites were established than are reported here. Test sites were eliminated for various reasons including high initial mortality, premature tree harvest, root rot (*Phytophthora* spp.), animal (rabbit/deer) and herbicide damage. None of the test sites received supplemental watering.

Each producer utilized production practices consistent with surrounding fields. These included weed control, fertilization, height control, side shearing, insect and disease controls as needed. For height control, typically, leaders remain uncut until trees reach 1.3 m in height. Cutting lengths for leader trimming depends on tree and bud density along with product goals established by each producer; but typically, are in the 25–35 cm range. All plants for a specific planting year were produced at the same nursery.

Tree measurements

Trees at each test site were evaluated following all cultural work in fall prior to the first harvest. The Washington test sites tended to develop more rapidly and in some cases, were evaluated 1 year prior to those in Oregon. Each test site had various intermediate evaluations not reported here. Final reported evaluations include measurements of the tree height, commercial tree grade, colour and value.

Tree heights

Reported tree sizes were measured from the ground to the top of a "properly" cut leader (measured to the nearest 2.5 cm) in the year of harvest. The "proper" height varied somewhat depending on bud structure along the leader but typically followed USDA guidelines (USDA 1992).

Grade

Tree grade is a quality assessment that combines a number of parameters including tree health, colour, uniformity of

density, and number of visible deformities across 4 quarter sections of each tree. Trees were categorized into one of five groups. The top quality grade is Premium. This grade is used sparingly on trees exhibiting superior colour, uniform full density with no tree health problems. The next grade category is a #1. These have the same characteristics as the Premium grade but are allowed one hole (18 cm or larger) resulting from limited branch cover. A #2 grade tree may have up to two holes in two quarters of the tree. Density may be slightly more variable. Colour is average. Although not defined within the fame of the USDA grading standards, but well known commercially, a Utility grade tree may have variable density in the upper 1/3 of the tree and holes, but is otherwise healthy. The lowest grade, Cull, as the name suggests, is not sold commercially and may be considered a liability. The grade is also divided in the data analysis into two derived categories: "best" meaning the proportion of trees having grade Premium or #1, and "standard" meaning the proportion of trees having grade #2 or Utility.

Colour

On each tree colour was evaluated against standard colour fans (Royal Horticulture Society 1966) and assigned one of three colour categories (5 = fan 181A- dark green blue; 3 = fan 138B- medium green; and 1 = fan 144A- greenish yellow). Typical evaluations were made with the sun to the back of the evaluator while averaging the colour in the upper 50% of the tree.

Value

Commercial production values were estimated for each tree based on the grade and height utilizing regional wholesale values. Heights in a commercial operation will be broken into 30 cm intervals with a value associated with each grade. In this evaluation, values were assigned to each 2.5 cm (inch) of tree height according to tree grade, that is, 0.23 Euro per 2.5 cm (assuming 1 USD = 0.8849 Euro), for Premium grade and 0.17, 0.12 and 0.08 for grade #1, #2 and Utility respectively. Grade values matched regional price averages in 2014 for noble fir. Three different estimates of marketable price were estimated: (a) Average sales value across all marketable trees; (b) Average sales value across all marketable trees including a penalty of 0.88 Euro per cull tree which is intended to mimic costs of tree removal and disposal; and (c), Average marketable value across all trees planted including a penalty (0.88 Euro) for cull trees and mortality. This gives an estimate of total sales revenue per ha when multiplied by number of trees planted per hectare (i.e. spacing 1.7*1.7 = 3460 trees per hectare).

Areas and seed sources

Native seed collection areas are associated with five ecological zonation's described by Randall (1996) and Randall and Berrand (2002) for noble fir. These areas are the Willapa Hills (WH), Washington Cascades (WCA), Oregon Coast (OC), Oregon Cascades (OCA) and S. Oregon Cascades (OCAS) (Figure 1 and Table 1). These are further subdivided into 16 smaller zones or provenances. Many of these will be reported as counties where the seed was gathered or smaller stands within counties. The "plus tree" designations in Table 1 are best described as superior phenotypes from broadly collected Coastal Oregon sources that were grafted into the Hostetler Seed Orchard (Dallas, OR) where seed was collected after trees matured.

Half-sibling crosses (hs)

Cones from 230 mother trees were collected from individuals either within each collection areas or from seed orchards with mother trees originating from those areas. In all cases, collections were made from trees exhibiting promising Christmas traits such are upright branching, good colour and high branch density.

Full-sibling crosses (fs)

These 21 crosses were all performed at the PNW Christmas Tree Association Hostetler Seed Orchard. All crosses are from parents native to the Oregon Coast.

Other seed stand collections (st)

One Oregon stand collection was made in the 482 Seed Zone from 1524 m elevation. This is within the S. Oregon Cascades in Lane County.

Danish (DK) seed sources included five seed stand harvests and one seed orchard, that is, FP623 C.E.Flensborg, from which four open-pollinated families were included. The specific origin of these sources is unknown, but is presumed to have been collected in the N. Oregon Cascades after the mid to late 1800s, planted in Scotland and Denmark and utilized/selected for greenery production.

Data analysis

Data were analysed using the SAS® software package version 9.3 (SAS 2010). The procedure Mixed/GLIMMIX was used for estimating components of variance and predicting area and provenance Best Linear Unbiased Predicted values (BLUP) as well as family breeding values. The following models were used analysing traits across planting years and test sites, but preceded by simple analyses of each test site within planting year (model not shown). Unless otherwise mentioned, all analyses were based on plot mean values – based on five or ten tree row plots.

Provenances

Each tree from open-pollinated or fullsib families could be referenced to a specific stand or harvest area – here referred as provenance. Across the planting years – these provenances were sampled, some multiple times, and the pooled performance of families was used as a proxy for the provenance. Additionally, harvest evaluations from other provenances including the Danish landrace were included in Table 1.

$$Y = \mu + t + b(s,t) + s(t) + p + p^{*}s(t) + p^{*}t + e,$$

where Y is plot value (mean or frequency), μ is grand mean, t is planting year, b is block, s is test site and $b(s,t)$ is block within test site and planting year, $s(t)$ is test site within planting year – all fixed effects, p is random effect of provenance, $p^{*}s(t)$ random effect of provenance and test site within planting

year interaction, and p^*t random effect of provenance and planting year interaction, e is random error variance and assumed normal, independent and identical distribution. The sampling nature of the provenances using the pooled families as a proxy for the provenance is no different from a traditional – across year random harvest of 10–20 trees per provenance (Williams et al. 2002). Because the intention of the study was to predict the performance of repeated harvest from these provenances for continued Christmas tree production – linear mixed models were applied and provenances were treated as a random effect.

Area and breeding values

Families within area were analysed using the following model, which does not include the Danish landraces:

$$Y = \mu + t + b(s,t) + s(t) + f(a) + a + a^*s(t) + a^*t + f(a)^*s(t) + f(a)^*t + e,$$

where Y is plot value (mean or frequency), μ is grand mean, t is planting year, b is block, s is test site and $b(s,t)$ block within test site and planting year, $s(t)$ is test site within planting year – all fixed effects, a is random effect of area, $f(a)$ is family within area, e is random error variance and assumed normal, independent and identical distribution.

The five geographic areas covers the entire natural ecological distribution of noble fir and as such classically would have been treated as a fixed effect, however, following the reasoning from the provenance model above, these areas are also potential seed harvest regions, they are sampled by the trees listed in Table 1, and it is our intention to evaluate the potential of these areas as future seed sources. Area then was treated as a random effect.

Model assumptions were evaluated by plotting residuals versus predicted values and testing for normality using the standard plots option. For both models the assumptions were fulfilled for the three traits of estimated gains in Euro, proportion of best trees and colour. Some deviations from normality of residuals were seen for cull trees and mortality, but hardly any deviations were seen for proportion of standard trees and commercial height. Significance of random model effects was tested using the difference of the log-likelihood ratio (multiplied by 2) comparing the full model and omitting one factor at a time from the model using a chi-square test and 1 degree of freedom (Gilmour et al. 2002).

Within plot variation (wi) was calculated separately applying a model of distinctive plot numbers across all test sites and planting years and estimating the overall plot variation and the error term being the within plot variation using the principles of Stonecypher (1992).

Breeding values (BV) were calculated based on family BLUP values using only the open-pollinated families and assuming a mixture of half- and fullsibs, that is, assuming a genetic correlation among offspring of 1/3 similar to Nordmann fir (Nielsen & Hansen 2010) instead of the theoretical value for true half-sibs of ¼ (Falconer 1989): $BV_i = r \times BLUP_i$, where $r = \sqrt{3}$.

Correlations between predicted breeding values were calculated as Pearson's correlation coefficient using the SAS procedure proc corr.

Heritability and gain

Assuming an average genetic correlation among offspring from the open-pollinated families of 1/3, as above, and following the principles of Zobel and Talbert (1984):

Narrow sense heritability $h^2 = 3 \times \sigma^2_{f(a)}/(\sigma^2_{f(a)} + \sigma^2_{f(a)*s(t)} + \sigma^2_{f(a)*t} + \sigma^2_e + \sigma^2_{wi})$.

Because the family model was based on plot means, to obtain the narrow sense single tree heritability the within plot variation, σ^2_{wi}, needs to be added to estimate the total phenotypic variation (Stonecypher 1992, p. 208).

Family heritability within area $h^2_{family} = \sigma^2_{f(a)}/(\sigma^2_{f(a)} + \sigma^2_{f(a)*s(t)}/\alpha + \sigma^2_{f(a)*t}/\beta + \sigma^2_e/(\alpha \times \beta \times \eta))$,

where α is the number of sites within trial, β is number of trials and η is number of reps within trial, suffix as described above.

Coefficient of variation (CVA) was estimated for genetic variation as: $CVA = \sqrt{3} \times \sigma_{f(a)}/\mu \times 100\%$.

Gain by selection, where Gain $= i \times h \times \sqrt{3} \times \sigma_{f(a)}$, where i is selection intensity, h is square root of narrow sense heritability and $\sigma_{f(a)}$ is family standard deviation (Falconer 1989).

Results

Site means

For all traits, highly significant test site differences were seen ($p < .001$), but differences were less for No. 2 + utility grade trees and height ($p = .011$) (Table 2).

Each planting year was comprised of different sources and test sites, except for 1–2 standard sources used across all planting years and sites. Each planting year there was a different percentage of best trees from a low of 17% to a high of 45% with a similar variation in values, height and other parameters. Though the difference in average heights appears small, this variation occurs across thousands of trees.

Mortality averaged 12%, but was highly variable from site to site (2–30%).

Also within test year on the specific sites, the variation in percent of the trees graded as Premium and #1 across all test sites ranged from 1% to 64%, and the wholesale value per tree planted ranged from 3.04 Euro to 12.85 Euro, reflecting a per hectare difference in total sales value of 33900 Euro (assuming a spacing of 1.7 by 1.7 m) between the best and worst sites (Table 2).

Provenances

Predicted values (BLUP) for provenances, Danish stand collections and PNW collections, were grouped within geographic areas (Table 1 and Figure 2). Furthermore, the components of variance for the random variation of the analyses were partitioned into effect of provenance and interactions with test site within planting year and planting year respectively (Table 3). For the evaluated traits, the highest proportion of the total random variance for provenance was seen for colour and height, where respectively 23% and 33%, of the random variation was due to provenance (Table 3). The

Table 2. Means (least square means) for all traits in the different test year series (trials), and overall site mean as well as minimum and maximum site means across all sites and years.

Test year trial	Grading			Mortality	Commercial height	Colour	Marketable value		
	Premium+ no. 1 %	No. 2 + utility %	cull %	%	cm	score	per sold tree + penalty cull euro	per sold tree euro	per planted tree euro
NF.1996	33%	51%	3%	12%	188	4.03	9.41	10.08	8.55
NF.2000	43%	40%	8%	10%	208	3.98	10.52	11.65	9.83
NF.2001	45%	45%	5%	5%	200	4.53	10.66	11.08	10.12
NF.2002	17%	50%	19%	14%	200	3.79	6.87	8.96	6.11
NF.2004	23%	51%	18%	8%	197	3.70	7.69	9.63	7.31
NF.2005	17%	53%	11%	20%	197	3.85	8.13	9.19	6.68
NF.2007	32%	51%	4%	13%	204	3.95	10.21	10.59	8.97
Overall LSmean	30%	49%	10%	12%	199	3.97	9.07	10.17	8.22
Site minimum	1%	23%	1%	2%	171	3.06	3.89	7.45	3.04
Site maximum	64%	64%	38%	30%	230	5.17	13.72	14.68	12.85
Fixed effects statistics									
block(planting year* test site)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
test site(planting year)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
planting year	0.000	0.011	0.000	0.000	0.011	0.000	0.000	0.000	0.000

Note: F-statistics and probability levels for fixed effect shown for replicates within site and trials, site within trial and trials.

marketable value traits showed random variance for provenance from 6% to 14%, whereas the proportion of Premium and #1 trees showed relatively more interaction with site and test year.

Generally, performance of provenances within an area are rather consistent (Figure 3). Provenances with the highest percent of Premium and #1 trees originated in the Coastal Mountains, which includes western Lewis County, WA, and Lincoln County, OR, which had a poorer performance. Overall, the Washington Cascades were intermediate and the Oregon Cascades and Danish provenances had the poorest quality. For commercial height, the Coastal sources and Washington Cascades were best; the Oregon Cascades and Danish sources showing lowest heights. In the Cascades, there is a tendency for slower growth moving from north to south. For marketable value, which combines height and grade, a similar pattern clearly specifies the Coastal sources as the best. The Danish sources stand out for superior colour. The selected seed orchard (FP623) and four families therein, as well as the stand collection F.710 Langesø had the bluest colour. The other Danish sources had a colour comparable with the Hood River provenance from Oregon, which was the only US source having a colour above mean (Figure 2).

Family and area variation

The family within area variance component comprises 6–8% of the total random variation for proportion of best trees, that is, Premium and #1 trees, colour, and marketable value estimates, but only half that for height. However, for height nearly half of the variation, 51%, could be assigned to harvest area, and 13% for best trees. For colour the area had hardly any importance (Table 4).

The estimated genetic coefficient of variation ranged from 24% for best trees, 6–10% for value estimates and as low as 2–4% for height and colour.

In general, the estimated narrow sense heritability's (within area) ranged from 0.02 to 0.06, although estimated family heritability's taking advantage of the design and replicates used in the study ranged from 0.64 to 0.79, omitting mortality, which didn't show any family variation.

Gain from backwards selection of tested mother trees was estimated using a selection intensity of 20 out of 200 based on the estimated components of variance. For proportion of best trees, a gain of 10 percent-units was estimated, and respectively a quarter of a scoring unit in colour and 6.0 cm in commercial height. Estimated gain in value estimates for sold trees and per planted tree ranged from 0.91 to 1.22 Euro per tree (Table 4).

The coast areas of Washington and Oregon (WH and OC) had the highest proportion of best trees, that is, Premium and #1 trees, the best commercial height together with the Washington Cascade, and the highest marketable value of sold trees. Hardly any area differences were seen for colour, but within each area bluer individuals can be selected (Figure 3).

The two most important economic traits, commercial height and Christmas tree grade, represented by the proportion of Premium and #1 trees, showed a positive correlation

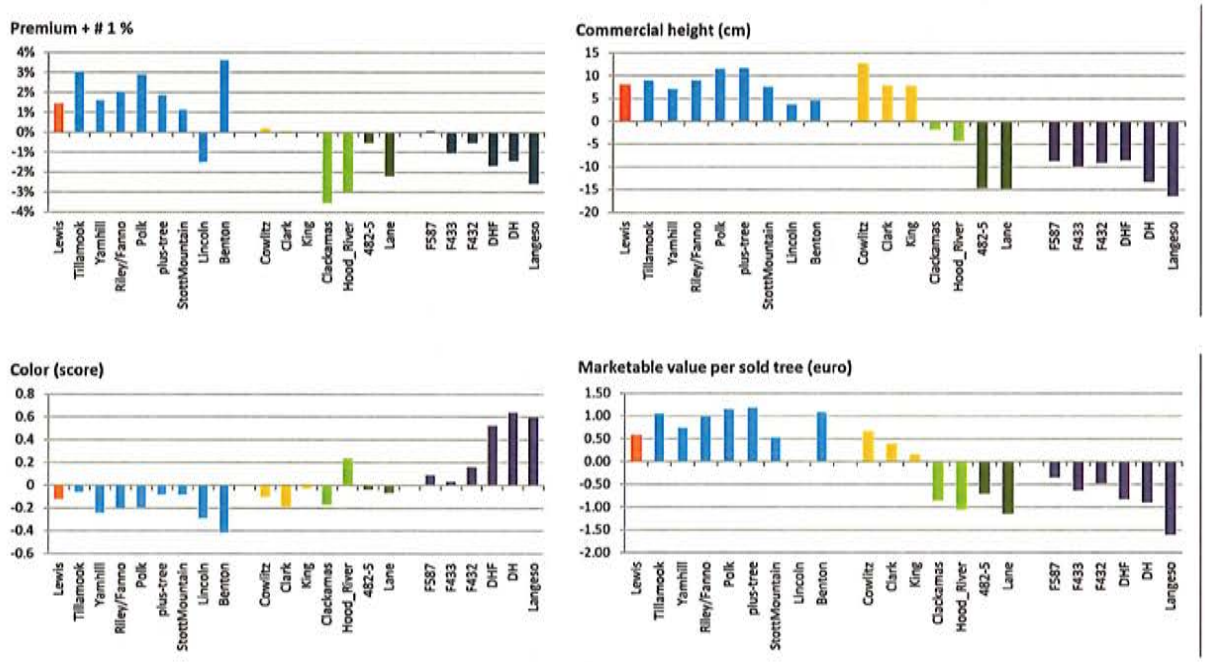

Figure 2. Predicted (BLUP) provenance values for each trait shown as deviation from overall mean: Quality grade as proportion of Premium and #1 trees (percent-units), commercial height (cm), colour (score) and marketable value per sold tree (Euro). US sources and Danish landraces, ordered by area from left Washington Coast (red), Oregon Coast (blue), then Washington Cascades (yellow), Oregon Cascades (light green), Southern Oregon Cascades (dark green) and Danish provenances (black).

Table 3. Components of variance for all traits across all trials and sites shown as percentage of total random variation.

	Grading			Mortality	Commercial	Colour	Marketable value		
Random variation	Premium+ no. 1 %	No. 2 + utility %	cull %	%	height cm	score	per sold tree + penalty cull euro	per sold tree euro	per planted tree euro
planting year*prov	7.5	0.6	3.6	0.7	9.6	3.5	11.1	9.6	10.4
test site*prov(planting year)	2.7	4.1	4.6	3.0	2.6	2.6	3.3	1.8	3.7
prov	2.6	1.9	0.0	1.0	33.4	22.8	5.6	14.2	5.8
Residual	87.2	93.5	91.8	95.3	54.5	71.0	79.9	74.4	80.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Overall mean	29.9%	48.7%	9.6%	11.8%	199	3.97	11.58	12.98	10.50

between breeding values (Figure 4). Colour of the needles seems independent of commercial height. Height can explain 52% of the market value, although it is an improper correlation due to the fact, that height is part of the value estimation.

For a commercial Christmas tree producer, it is highly useful to understand the important components that influence sales value. Ultimately, sales value relates both to commercial height and tree grade. In the PNW production system, value estimates are closely related to tree heights with R^2 values between 30% and 50% (Figure 4).

Colour on the other hand appears largely independent of both tree quality ($R^2 = .0034$) and height ($R^2 = .014$). Here it is important to note that average noble fir colours are green with yellowish trees being quite rare in these test sites.

Discussion

For the key traits important for Christmas tree production in the PNW system, that is, height and quality, there were large variations across the ecological areas where noble fir is found. Dividing the geographic range of noble fir into narrow as well as broader areas revealed important differences in growth, Christmas tree quality and sales value – which is of importance for commercial seed harvest as well for continued breeding activities.

Sites

Mortality across the 22 test sites varied from a low 2% to 30% with minor provenance differences (Table 2). Evaluated family and area effects were solely involved in interactions with test site and planting year. Tree mortality in commercial production is typically a function of first year moisture availability reflecting both weed management and summer/fall soil moisture. Both can vary site-to-site and year-to-year.

Site conditions strongly influence noble fir growth and survival as noted by Ying (1992) where 23 noble fir provenances were tested on 12 locations in coastal British Columbia. In this study, even rep within test site and trial where highly significant as was the test site within planting year. This suggests

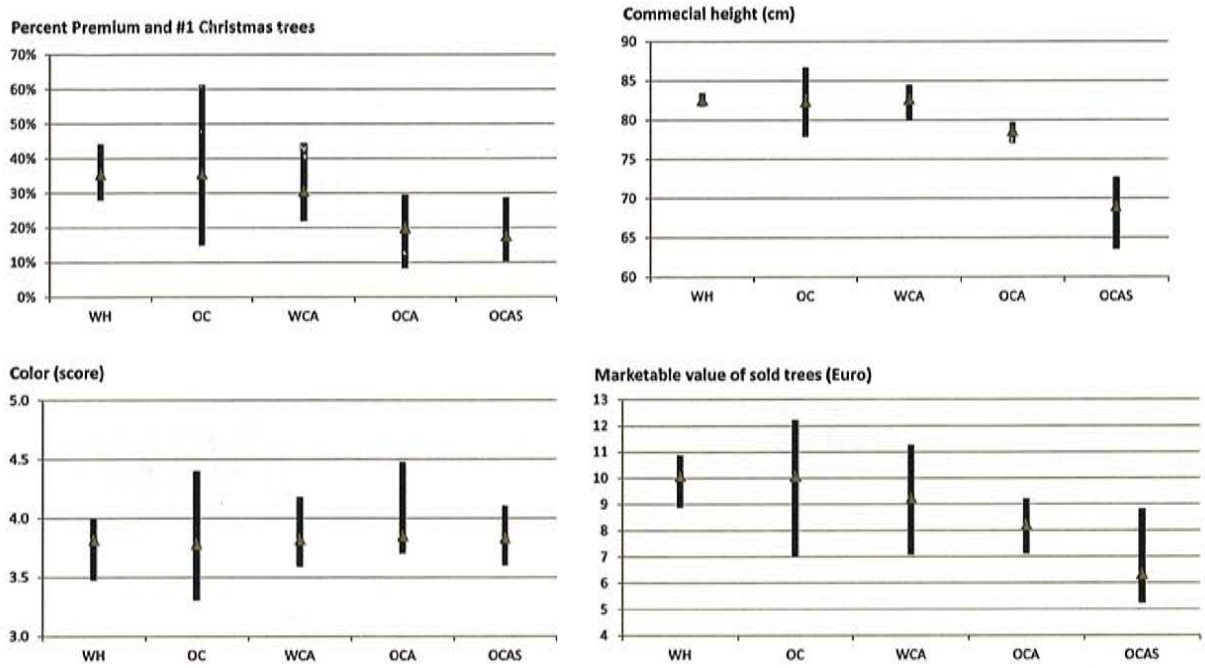

Figure 3. Predicted (BLUP) values for each area and range of lowest and highest predicted breeding value for families within each area – using a coefficient of relation of 3 assuming a mix of half-sib, full-sibs and selfings.

that micro site differences such as drainage or other environmental constraints as well as year to year rainfall will influence growth and time to harvest.

Area and provenance variation

Sorensen and others (1990) conclude that noble fir can be safely transferred rather long distances north-south as long as suitable planting sites are utilized. Randal and Berrang (2002) suggest that the natural distribution of noble fir in the Cascade Range (WCA and OCA in our study) be considered one seed transferr zone divided by an elevational band at 1200 m. The authors suggest the Willapa Hills (WH) remain a zone apart from the Oregon Coast with no elevational band. Our study found the Willapa Hills sources performed similarly to the Oregon Coast (OC) suggesting that these two zones could be considered ecologically similar.

In addition, this study supported the findings of Sorensen et al. (1990) in observing that the northern latitude sources (WCA) were on average taller than the more southern noble fir sources (OCA).

The S. Oregon Cascade sources (OCAS) were clearly different than any of the other four areas based on tree height and quality. This conclusion is supported by various studies of seed weights, terpenes and distribution of mistletoe suggesting that this area (around 44° N) begins the transition to Shasta fir (Sorensen et al. 1990; Mathiasen & Daugherty 2008; Oline 2008).

More broadly, Yeh and Hu (2005) identified a typical island (coastal) and mainland (Cascades-OR and WA) population

Table 4. Components of variance shown in percent of total random variance (based on plot means) for each trait, and also the within plot variation.

	Grading			Mortality	Commercial	Colour	Marketable value		
Variance components	Premium+ no.1 %	No. 2 + utility %	cull %	%	height cm	score	per sold tree + penalty cull euro	per sold tree euro	per planted tree euro
planting year*family(area)	3	0	0	0	6	3	4	7	4
planting year*area	0	0	0	2	0	0	0	0	0
test site*area(planting year)	1	3	5	5	2	5	3	1	4
family(area)	8	4	5	0	4	8	8	6	6
family(planting year*test site*area)	3	4	3	2	2	4	3	1	3
area	13	3	3	0	51	0	26	32	22
Residual	76	86	85	91	40	83	61	60	66
Total	100	100	100	100	100	100	100	100	100
within plot/total %	278	309	286	280	99	219	142	149	203
Overall mean across sites	0.28	0.49	0.10	0.12	200.7	3.8	8.79	10.09	7.96
CVA%	24	10	33	0	2	4	10	6	10
h^2	0.04	0.02	0.02	0.00	0.05	0.04	0.06	0.05	0.04
h^2fam	0.79	0.64	0.72	0.00	0.66	0.74	0.79	0.76	0.74
$i = 20/200$	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742	1.742
Gain fam	0.10	0.07	0.05	0.00	6.0	0.2	1.38	0.91	1.22

Note: Coefficient of genetic variation in percent, single tree narrow sense heritability, and a proxy for family heritability estimated for each trait and estimated gain from backwards selection for intensity of 20 out of 200.

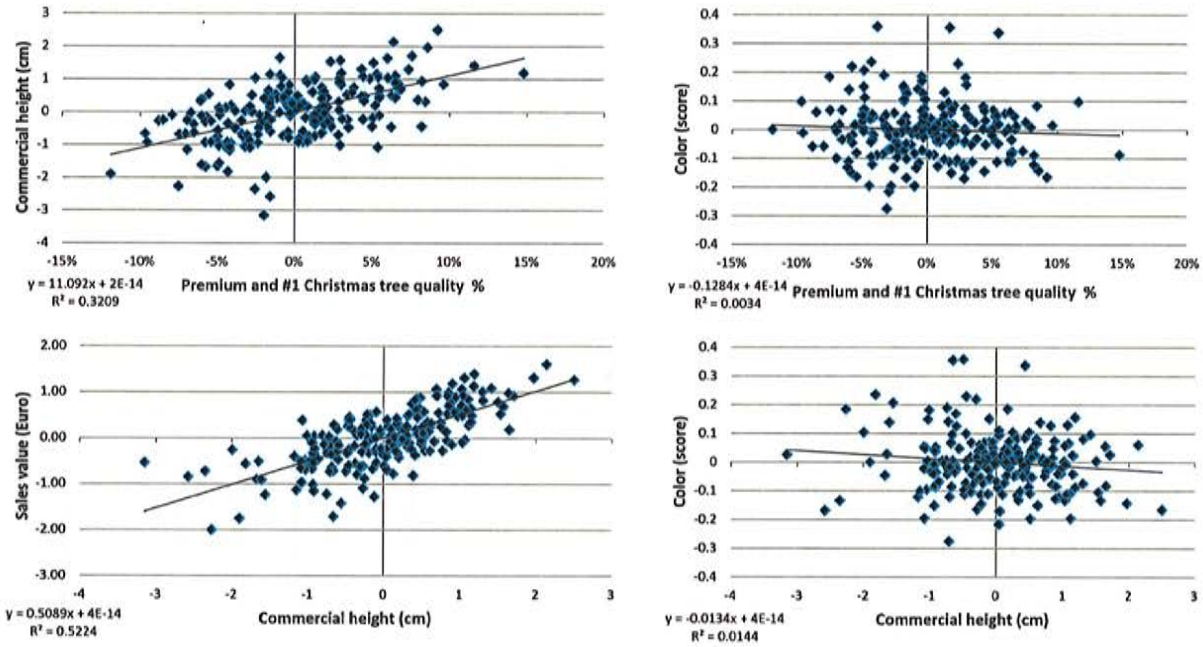

Figure 4. Pairwise plots based on predicted family values (BLUP) for each trait and family – shown as deviation from mean. A linear regression line is plotted for each comparison, also showing R-square values lower left corner. Sales value per sold tree (no penalty for cull's), commercial tree height (cm) and colour as scored value.

distribution for the noble fir based on an allozyme study. This study, in contrast, found a high level of consistency among the various coastal island populations with regard to height, grade and colour traits.

The Danish sources stand out for superior colour and slower growth. Both are traits important in the Danish bough production system and are key traits in their breeding programme. There is the hint of support for the Danish sources originating from near Mt. Hood since these also show better than average colour and slow growth. The Danish unselected stand sources approval numbers F.587, F.432, F.433 had a colour comparable to the Hood River provenance, which also might be one of the areas were the original selection were made. The FP.623 seed orchard consists of 100 clones phenotypically selected for blue colour and upright needles (HedeDanmark 2016) which definitely have improved average colour (Nielsen 2003). The F.710 Langesø originates from a grafted alley presumably of one very blue individual (Jakobsen 2015, pers. comm.) causing the bluish colour and slower growth possibly due to inbreeding depression (Sorensen & Miles 1982). However, based on vague historical information and the potential strong effects of selecting for blue colour, it is difficult to draw any precise conclusions on the origin of the Danish landrace. For example, Barner et al. (1980) reports that several imports occurred from 1854 to 1930s, when local, preferred seed was unavailable.

Breeding and family/area variation

Height and grade are the principal components of tree or stand value in Christmas tree production in the PNW. Conveniently, these are compatible traits so it is possible to identify trees or provenance areas where there is a higher probability of finding both. This, in part, is supported by Doede & Adams (1998) where they identified a positive genetic correlation of 0.33 between height and branch number. Larger number of branches are required to increase tree density, an important aspect of grade estimation. From this analysis, the Oregon Coast is broadly the region supplying the higher value opportunities with Tillamook, Riley/Fanno, Polk, Plus Tree and Benton being the provenances providing the highest market values (Figure 2).

In the initial phase of a breeding programme, first generation plus-tree selection is standard (White et al. 2007). In our case, similar phenotypic selections in noble fir Christmas tree stands are illustrated by the "plus tree" provenance. In this case, growers selected the best phenotype in a 1:1000 ratio from plantations of Coastal Oregon origins. The selected trees were grafted in orchards and seed later harvested for testing and production purposes. These selected plus trees from Christmas tree stands did have high average values, but surprisingly were, in general, not of any higher average values that trees collected in Tillamook, Riley/Fanno and Benton areas. The low estimated narrow sense single tree heritability's in this study underline the difficulty in simple phenotypic mass selecting. Estimated narrow sense heritability from other studies of Christmas trees indicate similar low values for Christmas tree quality, that is, Fraser fir (*Abies fraseri* (Pursh) Poir) 0.13 (Arnold et al. 1994); and, Nordmann fir (*Abies nordmaniana* (Steven) Spach) 0.10 (Hansen & McKinney 2010). However, seed orchards based on backwards selection could show a 7–10% improvement for grade which is in line with Arnold's (1994) finding for Fraser fir Christmas trees. Height growth genetic gain is expected to be a more modest 6.0 cm, yet spread across thousands of trees the gain is meaningful.

In conclusion, the production system in use has a strong influence on which trees are preferred in genetic selection. In

the PNW, rapid initial and consistent height growth is vital. Simultaneously, producers require trees that have a high grade. It is clear from this study the selected regions of the Oregon Coast appear to have a higher percent of both traits.

Important for future breeding potential in the PNW was the large variation in grade – especially the proportion of the best quality trees, that is, Premium and #1 (Table 4 and Figure 3). In the Oregon Coast material, the best selected tree provided 60% Premium and #1 trees compared to an average of around 35%.

In the Danish system, dark blue colour and slower growth are key traits. These traits are clearly evident in tree evaluations in the PNW. Though these traits are not key for most commercial Christmas tree operations in PNW, they could be quite important to bough producers and niche Christmas tree farms.

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