Planting Nonlocal Seed Sources of Loblolly Pine – Managing Benefits and Risks

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ABSTRACT: *Seed source testing of loblolly pine (*Pinus taeda*), which began in the 1920s, has allowed large realized genetic gains from using nonlocal seed sources in operational plantations. Seed source testing continues, and deployment guidelines are still being refined. Some general effects of seed source movement can be described, but there are still gaps in (1) understanding exactly how far certain seed sources can be moved, (2) the degree of risk involved, and (3) how certain traits such as wood quality vary by seed source, especially with seed source movement. In some cases, seed source movement gains can be achieved with little risk; for example, planting Livingston Parish, Louisiana material for rust resistance in more easterly Gulf Coastal areas. Also, movement of seed sources one plant hardiness zone north can result in increased growth with little concern for winter damage. Big gains in growth, however, from using nonlocal seed sources may come at significant risk. Two industrial examples of planting nonlocal seed sources and how risks were managed are covered: (1) South-to-north movement: MeadWestvaco's use of loblolly pine north of the native range in Kentucky and surrounding areas, and (2) East-to-west movement: Weyerhaeuser's use of North Carolina coastal plain families in southern Arkansas and southeast Oklahoma. To deal with the significant risks of seed source movements, one must be aware of the risk factors, understand historical climatic data (are the risks high or low within a typical harvest rotation period), and have silvicultural and genetic strategies to mitigate or reduce risk. Possible genetic strategies include thorough testing and allocation of orchard families of the nonlocal seed source, development of a "land race" (breeding and testing for local adaptation of the nonlocal seed source), interprovenance hybrids, and interspecific hybrids. Examples of these are discussed in this article. South. J. Appl. For. 29(2):96–104.*

Key Words: Seed source, genetic gain, adaptability, provenance, hybrid.

Importance of Nonlocal Seed Sources

Reasons for numerous cases of operational plantings of nonlocal seed sources in the southeastern United States on the part of private landowners include:

- Increased fusiform rust (*Cronartium quercuum*, (Berk.) Miy. Ex Shirai f. sp. *Fusiforme*) resistance. For example, planting of Livingston Parish, Louisiana material in high rust hazard areas of Florida, and southern Georgia, Mississippi, and Alabama.
- Increased growth rate. For example, moving material slightly north with low risk of winter damage and moving material west with low risk of drought damage.
- Increased survival. For example, planting drought-tolerant western sources on the sand hills of Georgia and Alabama.
- Use of improved families from sources that are more genetically advanced than the local seed source.
- No truly local seed source. For example, plantings just outside the loblolly natural range.
- No local seedlings for sale on the open market. Occasionally, a landowner may not be able to buy seedlings from a truly local seed source and must resort to the best alternative.

The old adage that "local is best" applies in the absence of information from well-conducted seed source trials but

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may not hold up once trial results are available. Due to the political circumstances that often surround local versus nonlocal seed sources, especially in the sale of seedlings to small private landowners, the Southern Forest Tree Improvement Committee (made up of university, state, federal, and industry forest geneticists) issued a SFTIC Position Statement in 1990 (unpublished). There were several points in that position statement all of which are still valid and useful today. Among them are:

"Uninformed use of local source is not necessarily either the best or safest choice." (Examples similar to those above are given). *"Genetic differences among seed sources provide an opportunity for informed landowners to increase yields by judicious matching of nonlocal sources to specific planting environments."*

Since seed source movement is a reality that is not likely to abate, the best course of action for the future is to ensure that the forestry community is well informed on the use of nonlocal seed sources and the risks thereof.

Historical Seed Source Study Results

The grandfather of all loblolly pine seed transfer studies was Philip C. Wakeley's Bogalusa, Louisiana, planting of 1927. The local Livingston Parish, Lousiana loblolly produced about twice the wood volume through age 22 as did the loblolly from Arkansas, Georgia, and Texas. These differences persisted through age 35 (Wakeley and Bercaw 1965), reinforcing the widely held belief that local seed sources are best. Differences in fusiform rust susceptibility were also observed, with the Texas and Arkansas sources being very resistant, the Livingston Parish being moderately resistant, and the Georgia source being susceptible. Wakeley's study had two important shortcomings. The test was planted in only one location, and it was not replicated.

The results of Wakeley's pioneering study led to the establishment of the Southwide Southern Pine Seed Source Study (SSPSSS), which was a cooperative effort initiated in 1951 by the Southern Forest Tree Improvement Committee. The early results of the SSPSSS gave the first indications that local sources may not be the best for growth and disease resistance (Wakeley 1961, Wells 1983, Wells and Wakeley 1966).

Similar types of seed source studies in other forest tree species indicated that sources from warmer climates tend to grow faster than local sources, if these sources are not moved to greatly differing climates. In loblolly pine, this is at least partly due to the warm-climate sources growing longer in the fall than the sources from colder climates (Jayawickrama et al. 1998a). Climatic modeling of data from many southern pine seed source studies has shown that the most important factor influencing growth and survival within their natural ranges is average yearly minimum temperature at the seed source (Schmidtling 2001). This climatic variable has been used, not coincidentally, by horticulturists to determine plant hardiness zones (USDA 1990).

As far as seed transfers are concerned, the most important observation made in the SSPSSS and reinforced by a study planted in southern Arkansas (Grigsby 1973, Wells and Lambeth 1983) was that the seed sources from west of the Mississippi River were more disease and drought resistant, but slower growing than eastern sources. The one exception to this East/West characterization is the well-known Livingston Parish, LA, loblolly, which is located just to the East of the Mississippi River. This source combines the fast growth, similar to eastern sources, and rust resistance similar to western sources. This situation undoubtedly derives from gene flow across the Mississippi River Valley in an eastward direction (Schmidtling et al. 1999).

Observations from these two studies and others have resulted in large-scale movement of seed sources east and west across the Mississippi River. In the eastward direction, loblolly pine from Livingston Parish, LA, and East Texas were planted in areas of high rust hazard in Mississippi, Alabama, Georgia, and Florida (Wells 1985). This was a very successful interim solution before rust-resistant strains of eastern seed sources were developed. In the westward direction, large quantities of Carolina Coastal Plain seed sources were planted in southern Arkansas (Lambeth et al. 1984). This has resulted in large gains in growth over local sources.

When grown in environments where their performance is not dramatically altered by maladaptation due to cold or drought, seed sources have the following traits, in general (Wakeley 1961, Wells and Wakeley 1966, Grigsby 1973, Wells and Lambeth 1983, Schmidtling 2001). Starting with northeast Florida seed collections and going to more northern or western sources:

- Growth rate: (as long as there are no maladaptations): Decreases strongly north and moderately west.
- Stem straightness: Increases strongly north and moderately west.
- Fusiform rust resistance: Increases moderately north and strongly west.
- Specific gravity: Although there have been a large number of reports of the effect of geography on specific gravity, there has been little work on provenance differences in loblolly pine as compared with the plethora of results for growth and rust resistance (Zobel and van Buijtenen 1989). The more definitive studies suggest it increases moderately both north and west (Jayawickrama et al. 1998a, Tauer and Loo-Dinkins 1990). This genetic trend is opposite to the plantation (geographic) trend. Specific gravity is often high in warm regions with high summer rainfall due to the longer growing season in those regions resulting in a higher proportion of summerwood in the ring (Zobel and van Buijtenen 1989). Therefore, plantations of Virginia seed source in Florida would have higher specific gravity than the native plantations.
- Cold tolerance: Increases very strongly north, no strong effect west within the same plant hardiness zone.
- Drought tolerance: Increases moderately west, no known effect north.

These trends are not always a gradual cline with latitude or longitude because the disjunct eastern and western populations are sometimes more different than the distance between them would suggest. This may be due to a different evolutionary migration of the two populations or a founder effect when the two were separated eons ago. Trends in seed source traits appear to be associated more with changes in climate, specifically temperature and rainfall, at the origin and seem to have little to do with soil type though they are not always completely independent (Schmidtling 2001).

The previously stated seed source differences are the rationale for attempts to attain greater plantation yield or quality through the use of nonlocal seed sources. However, there are known limits to seed source movement, some of which can be disastrous. Most notable of these is the fact that movements even moderate distances north can result in poor plantation performance. Again, a quote from the SFTIC Committee Position Statement:

> "*. . . seed source differences can be a potential problem for uninformed landowners who unknowingly plant an improper seed source. Lower yields and even plantation failures can result.*"

The conclusion thus far is that there are benefits to be had in using nonlocal seed sources, but there are definite risks. How does one go about making seed source decisions?

Considerations for Using Nonlocal Seed Sources

Considerations fall under two broad categories: What are the potential benefits and risks?

Benefits

Potential benefits must be evaluated in the context of the intended product with a thorough understanding of exactly what trait benefits can be derived for the intended product. Can the nonlocal seed source provide increased growth, quality, disease resistance, cold tolerance, or drought tolerance? A landowner who is primarily interested in high-quality lumber, for example, may do well to select sources with a high degree of straightness and favorable wood quality traits if wood quality will be valued in the marketplace at harvest time.

Cost and gain are two critical components in financial decision-making. However, the differential cost of seedlings in today's market will rarely be large enough alone to weigh heavily in decisions of whether or not to plant a nonlocal seed source. Nonetheless, cost is a component in the overall equation and must be considered.

Financial benefits should be understood as clearly as possible to weigh risk appropriately before purchasing nonlocal seed sources, especially if there is a significant risk involved. Landowners who purchase genetically improved planting stock and do not have their own seed source trials should insist on useful information that can be converted to an estimate of financial benefit.

Risks and Silvicultural Practices to Mitigate Them

- Maladaptation: What are the potential downsides in terms of cold or drought damage based on historical seed source movement trials?
- Rotation: Risk of loss due to environmental extremes cannot be separated from the harvest cycle time. Losses near rotation age are more significant when the rotation is long.
- Silviculture: Silvicultural practices can mitigate some risks. For example, soil preparation, planting density, and weed control can alleviate moisture stress associated with maladaptation to drought. There is some evidence that proper nutritional balance can reduce moisture stress (Troth et al. 1986). Because tree vigor and southern pine beetle (*Dendroctonus frontalis* Zimm.) resistance are favorably correlated (Roberds et al. 2004), enhanced nutrient status may aid in overall tree health, which could improve insect resistance. Thus, fertilization can be a valuable tool in seed source risk reduction.
- Historical climate perspective: Because forest crops are long-term in nature, it is necessary to study historical patterns to fully understand risks associated with extreme climates, especially when moving seed sources long distances. What are the most extreme conditions that could occur during the rotation and how often do they occur? Fifty years of climatic data are not too much.
- Testing information: Is there test information in the target planting area for the nonlocal seed source? How sound is it and what do the results say about risk?
- Ability to absorb loss: Small private landowners obviously cannot take the same risks that a large industrial landowner can. The latter has several thousands of hectares of stands of different ages and can absorb losses more easily than some smaller private landowners for whom the loss of even a few hundred trees could be a disaster.
- Other uncertainties: The old saying that "all of the information is never in" holds in the area of seed source movement. Most testing systems are not perfect. The prospects for and effects of global warming are poorly understood, but some models predict that some areas will become more droughty under some scenarios which could have implications for considering drought tolerance in choice of provenance. Also, what other traits may be of interest in the future that have not yet been characterized in the various seed sources. For example, are there seed source differences in microfibril angle or cellulose yield per dry ton?

Guidelines and Industrial Examples of Seed Source Movement

Decades of seed source testing have produced results that can aid in deciding whether or not to plant nonlocal seed sources. Some simple guidelines are below. The recent USDA Forest Service Publication *Southern Pine Seed*

Sources (Schmidtling 2001) is an excellent source of information on this topic. We also present two industrial cases of wide seed source movements (one south to north and the other east to west) that do not fit the standard guidelines for seed source movement. In both cases, there was a very significant potential benefit, and risks were mitigated with one or more tree improvement and/or silvicultural management strategies.

North-South Movements

The benefits of moving loblolly pine seed sources north are well-known. Seed sources moved a modest distance northward often outperform seeds from the local source (Wells and Wakeley 1966). If moved too far north, however, they suffer cold damage and do not perform as well as the local source. If northern sources are moved south, they do not grow as fast as the local source.

Climatic modeling of north-south transfers of loblolly seed has shown that yearly average minimum temperature, the most important climatic variable related to growth and survival, defines the rules of seed movement (Schmidtling 2001). This variable, which defines "plant hardiness zones," has been used for many years by horticulturists to guide the transfer of plant materials. The model predicts that a transfer of seed northward by 5° F in minimum winter temperature is optimum for increased growth over local sources. A transfer of more than 10° F minimum winter temperature results in cold damage and growth that is less than the local sources.

There is little incentive for moving loblolly pine seed sources southward because of reduced growth, but for years, loblolly pine has been extensively planted north of it's natural range, with varying degrees of success (Parker 1950). Typically, in long-term tests, height growth varies little, but survival differs greatly among sources, especially in later years.

In a provenance test in southern Illinois, a coastal South Carolina source grew well and had satisfactory survival after 5 years (Wisehuegel 1955), and after 10 years (Zarger 1961). By 35 years, however, only 3% of this source survived, compared with between 33% and 42% for sources from the northern extremities of the natural loblolly pine range: Tennessee, northern Alabama, and northern Georgia (Wells and Rink 1984). The southern Illinois location of this test represents a move of about 7° or 8° F north of the origin of the Tennessee source. Height growth of the surviving trees did not vary significantly among the seed sources.

Minckler (1950) established a similar experiment in two slightly colder locations in southern Illinois. After 27 years, survival of sources from Maryland, Virginia, and Arkansas was about 60%, compared with about 40% for sources from the Carolinas and Mississippi (Gilmore and Funk 1976). After 37 years, survival was unsatisfactory for all sources, averaging only 14% (Rink and Wells 1988). Height differences were not significant. The most hardy sources from Tennessee, northern Alabama, and northern Georgia included in the Wisehuegel (1955) experiment were not used in this study. The Maryland source in this experiment is the most cold-hardy source measured by minimum winter temperature. The two locations used in this study represent move to a climate colder than the Maryland origin of 11° t 15°; the other sources were from even warmer locations.

Gilmore (1980) recommended that loblolly pine not b planted north of the 180-day contour of frost-free days i Illinois. He noted that a 30-year-old planting of a Marylan source just 60 miles north of this contour suffered almos complete mortality in the record freeze of 1977. Because th mortality was related to freeze damage, it would seem mor reasonable to use average minimum temperatures to guid seed movement rather than growing season length. In Illi nois, the 180-day contour is just north of the −10° isotherm of minimum temperature. For a Maryland source from Worchester County, this would be a move to a climat colder by more than 15° F. minimum temperature. For ever the most cold-hardy sources, this represents a move of mor than 10°. Gilmore's recommendation may not be conserva tive enough except for the most cold-hardy sources.

Industry Example

A very small number of companies have tried to extend the northern limits of loblolly pine's native range. In most cases, these have met with failure due to a number of reasons, including the inability to recognize that no single provenance or seed source is suitable for extreme northern extension and that environmental stress factors (in this case cold) are extremely nonuniform. Loblolly pine can be moved significantly north of its native range without detrimental effects if care is taken to understand the environment and conditions that will affect survival and growth. In the more northern environments of the southeastern United States, the most limiting factors are cold and resistance to ice and snow loads. Although a variety of laboratory techniques have been examined as a means of defining cold hardiness (Kolb and Steiner 1985, Hodge and Weir 1993, Aitken and Adams 1997), none have taken the place of long-term field trials. Unfortunately, the impact of cold cannot be simply defined as lower winter temperatures. The fact that the physiological status of the tree plays a critical role in defining the genotype's ability to withstand cold temperatures can be easily overlooked resulting in rather poor selections. This is then dramatically compounded by establishment of plantations with genetic material whose suitability could be hidden for a number of years because of the infrequency of cold events.

The overall impact of cold is comprised of a number of environmental factors that are closely intertwined. These factors include late season growing stress (such as drought), mild fall and early winter temperatures, and rapidly falling winter temperatures (40 to 50° F within a 24-hr period) that are accompanied by high winds. The combination of these factors results in a significant cold event that will have an immediate and devastating effect on unsuitable sources and families. However, this type of cold event will only occur two to three times during a 20- to 30-year rotation. In many cases, these factors will combine, causing nonvisible cumulative damage that will eventually result in performance

rank changes. Although long-term field-testing is costly, it is the only method that insures selection of the best-adapted seed source.

Westvaco (now MeadWestvaco) has been successful in its approach to the operational use of loblolly pine north of its native range. The development of cold-hardy loblolly pine was preceded by the development of pitch x loblolly pine hybrids. This work was begun as a cooperative agreement in 1963 between USDA Forest Service Northeast Forest Experiment Station and Westvaco (Little and Trew 1978). Westvaco established a number of pitch x loblolly pine hybrid tests in Kentucky, Virginia, and West Virginia during the 1970s and 1980s in conjunction with loblolly pine trials to compare the possibility of moving loblolly northward. Studies were established by Westvaco's Central Forest Research Center during the early 1970s in Livingston County, Kentucky, and McNairy County, Tennessee (Barbour 1972a, 1972b and Barbour 1980). Prior to any significant cold event, loblolly sources from the Atlantic Coastal Plain and Lower Gulf Coastal Plain outperformed the more northern sources from the South Carolina piedmont and Virginia. However, the more southerly coastal sources suffered extensive foliage and cambial damage following significant cold events. In many cases, damage resulted in mortality during that same year or a weakening of the tree from which it never recovered. Foliage and terminal damage was more evident in trees between ages one and eight. This type of damage is very visible in the late winter or early spring. Within-source variation among the more northern Virginia and Piedmont sources was significant, indicating that selections could be made for cold resistance. Additional exploratory tests indicated that cold-hardy selections could be made from all of the northern provenances.

As is generally the case, Westvaco's operational plantings and research genetic trials were established at the same time in the early 70's. Except for the most southerly or lower coastal plain material, almost any native loblolly material could be grown effectively in the Appomattox, Virginia area and the southwest Tennessee counties of Chester, Hardeman, Henderson, and Madison. However, further extension of loblolly into Tennessee and Kentucky was needed to reduce the cost of transportation to Westvaco's mill in western Kentucky. In addition, movement of loblolly pine into the Parkersburg, West Virginia area to support the Luke, Maryland mill dictated additional testing.

Initially, cold resistance was thought to be highly correlated with slow growth rates. Many of the initial cold-hardy selections exhibited rather poor growth performance when grown within the native range. However, inclusion of higher census numbers within the test population has led to a rethinking of this correlation. Unfortunately, numbers of trees within a select population are still not at the point where a large-scale breeding population can be formed, but an elite breeding population would certainly fit this rather limited scale program. Specific mating designs could be used to take advantage of the slight variation that exists outside of the native range.

Continued selection efforts have developed cold-hardy loblolly pine that survive and grow in cold environments previously thought to be too inhospitable for loblolly pine. Defined deployment zones are based on the amount of cold resistance needed for survival and rapid growth. Today, cold-hardy sources can be grown in close proximity to the mills, thus lowering transportation cost. In addition, loblolly pine proved to be faster growing than either shortleaf pine (*Pinus echinata*) or pitch (*Pinus rigida*) x loblolly hybrid, thus allowing for shorter rotations. The primary risk remains the uncertainty of the environment. Unprecedented mortality from southern pine beetle occurred in 2001 in northern plantations of loblolly pine along the Cumberland Plateau in Tennessee. To date, we have not seen southern pine beetles in the more northern stands in Tennessee and Kentucky, but that may be because of restricted movement of the beetle. The size of the deployment population is also somewhat of a risk, but this seems comparable to the limited deployment of genotypes followed in the native range of loblolly pine.

East-West Movements

In this section we refer to movements east to west or vice versa within the same plant hardiness zone. This type of movement is more common and usually entails little climatic risk except in the case of movement of seed sources from high rainfall areas to areas that experience frequent drought along the western fringe of the loblolly natural range. For example, planting South Georgia seed source in southeast Texas or North Carolina material in southwest Arkansas and Oklahoma should be viewed as a significant risk. In one study in southeast Texas, no East Coast seed sources produced as much volume per hectare as the local source in four 20-year-old, unthinned plantings, two of which were outside the loblolly pine natural range (Long 1980). On the other hand, movement of material from South Georgia to southeastern Louisiana or from central Louisiana to East Texas may not entail significant risk.

Some less risky but beneficial moves in this category have already been mentioned – planting of Livingston Parish, Louisiana material in high rust hazard areas of Florida, and southern Georgia, Mississippi, and Alabama (Wells 1985) and southwest Texas material in the sandhills of Georgia and Alabama for drought resistance (Jett and Guiness 1992). Another common movement is to plant more easterly coastal sources moderate distances west, which results in significant gains in growth rate at little risk – for example, Georgia coastal sources in coastal Mississippi and Alabama and Carolinas coastal material in central Georgia and Alabama (Schmidtling 2001, Sierra-Lucero et al. 2002).

In a recent study (Sierra-Lucero et al. 2002), Gulf coastal plain sources (GCP, i.e., lower Mississippi and Alabama) gave unexpectedly poor performance compared with north Florida and lower Atlantic coastal plain sources (Agricultural Conservation Program (ACP)). Until recently, most tree breeders have considered the GCP and ACP as comparable provenances for growth (e.g., Lantz and Kraus 1987). In general, provenance growth performance for

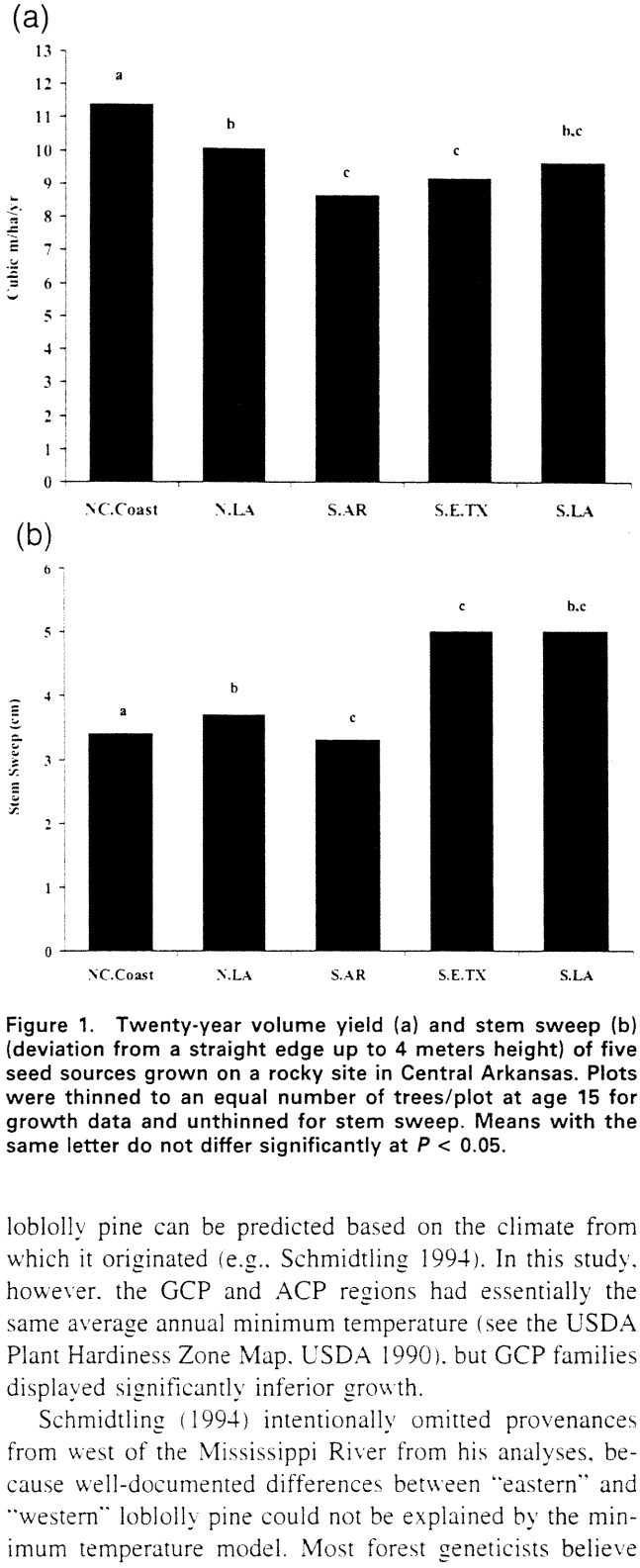

Figure 1. Twenty-year volume yield (a) and stem sweep (b) (deviation from a straight edge up to 4 meters height) of five seed sources grown on a rocky site in Central Arkansas. Plots were thinned to an equal number of trees/plot at age 15 for growth data and unthinned for stem sweep. Means with the same letter do not differ significantly at $P < 0.05$.

loblolly pine can be predicted based on the climate from which it originated (e.g., Schmidtling 1994). In this study, however, the GCP and ACP regions had essentially the same average annual minimum temperature (see the USDA Plant Hardiness Zone Map, USDA 1990), but GCP families displayed significantly inferior growth.

Schmidtling (1994) intentionally omitted provenances from west of the Mississippi River from his analyses, because well-documented differences between "eastern" and "western" loblolly pine could not be explained by the minimum temperature model. Most forest geneticists believe that the east-west differences in loblolly pine (i.e., the slower growth of western sources) are due to selection for drought tolerance west of the Mississippi River as well as introgression with shortleaf pine (e.g., Florence and Hicks 1980, Wells 1983). We speculate that the east-west trend seen across the Mississippi River may also exist in the eastern part of the range. Squillace and Wells (1981) showed that limonene had a strong east-west gradient both across the Mississippi River (large percentage of trees with high limonene in the west and lower percentage of tree with high limonene in the east) and in the eastern part of th loblolly pine range. High limonene was found in 25% t 50% of the trees in the GCP and in 0% to 10% of the tree in ACP sources.

Molecular marker analyses have shown that gene flo from west to east has not been restricted by the Mississipp River (Schmidtling et al. 1999, Al-Rabab'ah and Williar 2002). Thus, the geographic pattern of variation for lobloll pine in the eastern part of the range that does not seem to b based on climatic or edaphic factors can likely be explaine in part by this west to east migration. The unexpected poo growth of the GCP may be due to gene flow from slowe growing sources on the western side of the Mississipp River.

Industry Example

In 1972, Weyerhaeuser Company began testing c coastal North Carolina (NC) families on its 600,000 hec ares of land in southwest Arkansas and southeast Oklahom (AR/OK). By the late 1970s, trials were showing a ver large growth advantage of those families over the loc source – roughly 20% in projected volume per hectare gai due to seed source movement alone plus additional gair from more advanced genetics (e.g., Figure 1). These result along with those from two rangewide seed source tria planted by the USDA Forest Service in the late 195((Grigsby 1973), resulted in a decision to plant commerci plantations of the nonlocal source in the coastal plain soi that comprised 25% of the land base. The other 75% ar Quachita mountain soils that can often be rocky and hav low water holding capacity. It was recognized that th planting of NC coastal material, which comes from ver deep and often poorly drained soils and relatively hig summer rainfall, into an area with a more frequent drougl occurrence entailed some risk, but the risk was initiall poorly understood. Nonetheless, the sizeable difference i growth rate over the local source, which was known to b the slowest growing of all loblolly pine, seemed to justif the risk. Increased winter damage was thought to be nom inal since the NC seed source of interest lies within the sam plant hardiness band, and trials had indicated little diffe ence between the local and nonlocal seed sources for bot freeze and ice damage during severe winters (Jones an Wells 1969, Burris et al. 1982). Also, the fact that the N trees are routinely very straight in many trials, in compar son to the local source, is further indirect evidence that the are adapted to the occasional ice and snowstorms in th area. More southerly sources suffer in this regard (Figure 1

In 1980, one of the worst droughts on record provided a opportunity to better quantify the drought risk by see source. Results indicated higher drought mortality in the N seed source, as did greenhouse stress tests (Burns et a 1982, Lambeth and Burris 1983, Lambeth et al. 1984 However, the overall mortality levels were low and ap peared to occur more on soils with low water holdin capacity. The principal problem is mortality after stan establishment, and not first-year mortality that is strongl

influenced by nursery culture. The local and nonlocal sources do not differ greatly in first-year survival. Based on the 1980 drought results, the decision was made in 1983 to extend the planting of NC material onto deeper mountain soils, some of which are just outside of the northern and western limits of the natural range of loblolly pine. This decision led to planting 60% of all company lands in Arkansas and Oklahoma to the NC seed source.

Since 1973, approximately 150 Weyerhaeuser trials comparing eastern and AR/OK seed sources have been installed, including progeny tests of over 400 parents. The growth rate of the NC source, almost without exception, significantly exceeds that of the local seed source, even on the shallowest and most rocky soils. During that period, there have been six significant drought years that have provided the opportunity to clarify the risk of planting NC material. Surveys of drought-related mortality are conducted in these progeny tests and in the thousands of commercial plantations of nonlocal families that have accumulated over the years. Surveys indicate that drought mortality is higher in Oklahoma than southwest Arkansas in most drought years and is not related to soil water holding capacity, i.e., there were no detectable trends of seed source mortality differences being greater on shallower soils.

Each year for 10 years and now during drought years only, 26 commercial plantations (20–80 hectares each) per seed source per each of two regions (southwest Arkansas and southeast Oklahoma) are surveyed by helicopter, and a complete count of dead trees is made. The number of dead trees is divided by the number of trees during the last inventory to get percent mortality. These surveys reveal that (1) even in a severe drought year, such as 1998, mortality in the NC seed source is low and (2) even the local seed source is subject to drought mortality (Figure 2), although at a lower rate.

There have been worse drought periods than have been experienced in the past 20 years. Attempts have been made to model what might happen during such a period assuming a "worst case" approach (worse than what has been observed) in terms of mortality as a function of soil moisture deficit for the NC seed source versus the local seed source. Growth and yield modeling of worst case scenarios have indicated that it is highly unlikely that the significant growth advantage of the NC seed source over the local source would be lost, even in a worst case situation.

Some additional actions that are being taken by Weyerhaeuser to understand or reduce the risk are:

Genetic

- Families are tested on a variety of sites and straightness and growth are key selection variables.
- Only nonlocal orchard families that have been progeny tested in the area are planted commercially, and they are planted in family blocks for observation purposes.
- Families that do not perform well during drought surveys are no longer deployed, but only a few families have been eliminated on this basis.

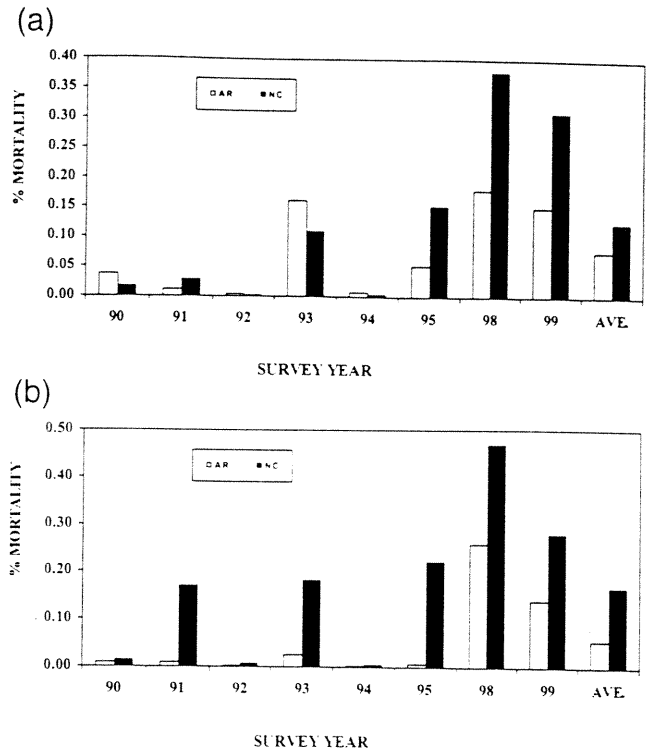

Figure 2. Mortality for Arkansas and North Carolina seed sources from aerial surveys in operational settings in southeast Oklahoma (a) and southwest Arkansas (b). Settings were 20 to 80 hectares each and 26 settings per seed source per year.

- Individual trees within the best families have been selected on very tough sites and form the foundation of a "land race." These select trees have been bred and their progeny are under test.
- Future orchards of nonlocal material (land-race derived) will be located in Arkansas so as to be contaminated by local rather than nonadapted, nonlocal pollen in North Carolina.
- Interprovenance hybrids are being testing for potential complementarity of growth rate and drought resistance.

Environmental and Silviculture

- Mortality surveys during droughts continue.
- Climatic data are updated and each year soil moisture deficits are calculated to understand the levels of stress that produce mortality.
- Site preparation by means of ripping a trench or tillage on the contour is aimed at ensuring adequate moisture during the early establishment years by providing the seedling good soil structure for root penetration and capture of moisture in the rip.
- Fertilization throughout the rotation helps keep trees nutritionally balanced and thus less prone to stress and/or beetle attack.
- Stand densities are low by comparison to many stands throughout the southeastern United States, which hopefully reduces stress as well.
- Herbaceous weeds and hardwood control can reduce moisture stress, especially in early years.

Mitigating Seed Source Movement through Tree Improvement

There are some promising tree improvement strategies that can reduce the risk of planting nonlocal seed sources: Testing families for adaptation: Thorough testing for adaptation under climatic extremes can help identify potentially poor families that should be eliminated from planting programs and from seed orchards.

Land race development: Breeding and testing of the nonlocal seed source for adaptation to the exotic environment can be a very effective way to increase adaptability and reduce risk. The resultant improved material is known as a "land race" (Zobel and Talbert 1984). Examples of this were given in the two industrial case studies above.

Species and interprovenance hybrids: Interspecific hybridization can be a very effective way to lower risk of loss due to climatic extremes. Interprovenance hybrids have been less explored, but a recent greenhouse study indicated that it might be possible to increase adaptability without losing growth rate when hybridizing fast growing East coast selections with slower growing but more drought-tolerant families. Figure 3 shows growth and survival results from a greenhouse stress test. In the stress test, seedlings were grown for approximately seven months in sand boxes, and then water was gradually withheld until trees began to die (Burns et al. 1982). When approximately half of the seedlings were dead, the test was rewatered and actual survival counts were made once seedlings had a chance to recuperate.

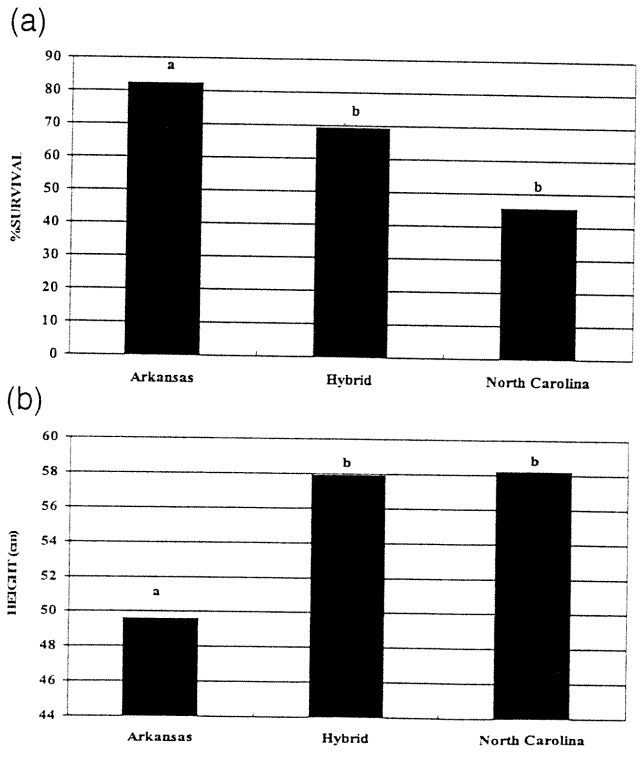

Figure 3. Survival (a) and growth (b) of Arkansas, North Carolina, and AR x NC hybrid seedlings of loblolly in a greenhouse moisture stress test. Means with the same letter do not differ significantly at $P < 0.05$.

Another study showed that crossing fusiform rust-resistant provenances with fast-growing provenances can provide complementary combinations of the two traits, and there was some evidence of heterosis as well (Schmidtling and Nelson 1996). Advances in control-mass-pollination now make these two options more feasible as commercial applications.

Cloning: Adaptation differences among families within a nonlocal seed source suggest differences among clones within the best families, an avenue that will be exploited as clones become widely planted throughout the range of loblolly pine. However, with no genetic variation within a clone for buffering against climatic extremes, clones must be very thoroughly tested, more so in the exotic environment than in its native area. Testing should be thorough both in terms of the number of sites and in terms of a longer field assessment.

Conclusions

In many regions of the South, use of nonlocal sources of loblolly pine has become the standard rather than the exception. For example, in the North Carolina State University – Industry Cooperative Tree Improvement Program, most companies and state forestry organizations in the Gulf coastal plain region plant Atlantic coastal plain sources of loblolly pine rather than the local source. The well-documented growth advantage of the ACP provenance (e.g., Sierra-Lucero et al. 2002) and the low risk from pests and climatic factors make the use of the nonlocal provenance an economically attractive decision in this region. Increased growth, reduction in fusiform rust disease, improved cold or drought tolerance, and better stem form and wood quality are all realized benefits from using well-tested, nonlocal provenances. Although the benefits of seed source movement are relatively easy to show, we have emphasized that there are substantial risks associated with the use of some exotic sources. Long-term, well-designed field trials are critical to understand risks.

Use of nonlocal sources is frequently used in conjunction with silvicultural systems designed to reduce environmental stresses, which may include spacing, fertilization, intense site preparation, and increased monitoring. Landowners not willing or capable of implementing these measures will experience increased risk.

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