Conifer Translational Genomics Network Coordinated Agricultural Project

Genomics in Tree Breeding and Forest Ecosystem Management

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Module 12 – Marker Informed Breeding (MIB) – Program Management

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www.pinegenome.org/ctgn

Marker applications

- Quality control
- Introgression and hybrid breeding
- Parentage analysis
 Pollen contamination
- Enhanced breeding designs



Quality control in a clonal seed orchard



Figure Credit: Nicholas Wheeler, Oregon State University



Opportunity cost of orchard errors

Assume

- Progeny of wrong orchard clone have 5% less genetic gain (volume) than progeny of desired clone
- 1% gain = \$10 present value/acre planted (\$60 future value at rotation)
- Annual planting requirement = 10,000 acres, of which 10% is planted with the desired clone (1000 acres)
- 40% of trees in desired clone are mislabeled; thus, 400 acres per year are planted with trees that are performing 5% below expected
- 400 acres * 5% * \$10/acre/percent = \$20,000 present value (\$120K future value). If unchecked for 15 years, = \$300K present value



Marker assisted backcrossing or introgression

- This is easily the single greatest application of markers to animal and plant breeding in the world
- Used predominantly for simply inherited traits such as disease or insect resistance
- Commonly used to introduce an important allele from an unimproved individual / species into a highly selected individual / line / variety



Backcross breeding approaches

- Marker-assisted "foreground" selection
 - Select for markers that identify favorable alleles from the donor population
 - Markers must be in very tight linkage with desired trait
- Marker-assisted "background" selection
 - Select for marker alleles that identify the host (recurrent) parent genome
 - Must have many alleles with complete genome coverage
- Typically, both approaches are used together



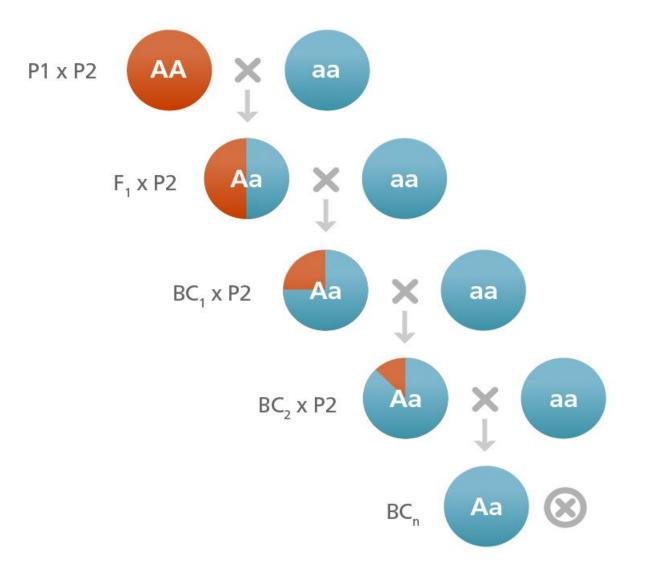


Figure Credit: Modified from Welz and Geiger, 2000



Distribution of genotypes in simulated BC₁ population: recovery of RP genome

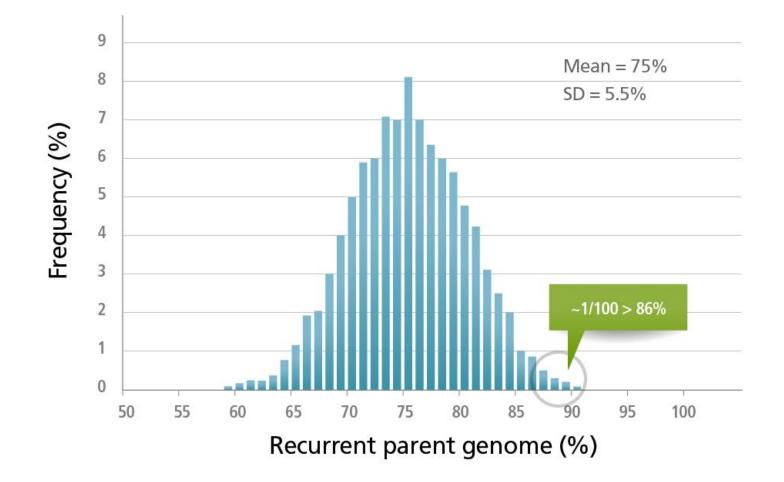


Figure Credit: Modified from Welz and Geiger, 2000



American chestnut

- Early in the 20th century, the Appalachian Mountains were full of giant chestnut trees
- Chestnuts were abundant, accounting for 25% of all Appalachian hardwoods
- Tree diameters of 8 to 10 feet were often reported. One in Francis Cove, North Carolina, was 17 feet in diameter
- Chestnut grew tall (up to 120 feet) and straight -- often clear of branches up to 50 feet, making them ideal lumber



Image Credit: John Carlson, The Pennsylvania State University and The American Chustnut Foundation.



American chestnut



Image Credits: John Carlson, The Pennsylvania State University and The American Chestnut Foundation



American chestnut

- Chestnut was an important commodity for the early European settlers of the Appalachians
- Uses included
 - Nuts for food, mast, and cash
 - Tanning hides
 - Building materials





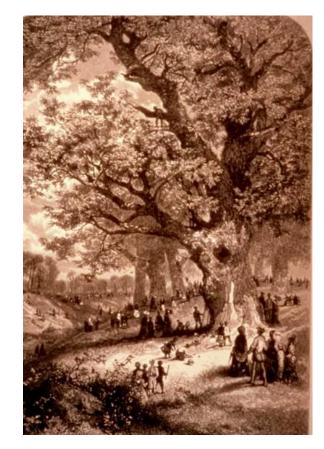


Image Credits: John Carlson, The Pennsylvania State University and The American Chestnut Foundation



The chestnut blight

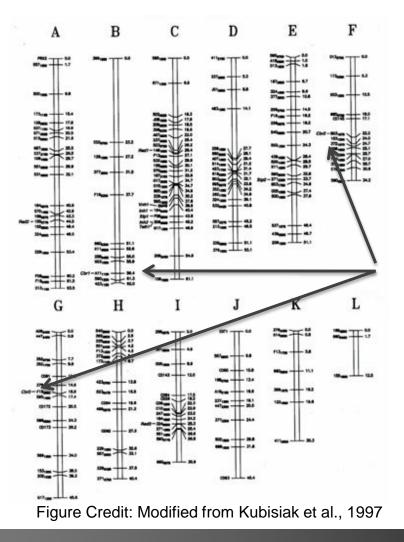
 By the 1950s, chestnut was virtually eliminated as a dominant forest tree



Image Credits: John Carlson, The Pennsylvania State University and The American Chestnut Foundation



QTL studies reveal three sources of major resistance





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Marker applications in chestnut restoration

- Quality control in breed orchards
- Genetic mapping
- QTL mapping
- Marker informed introgression
- Locating resistance genes



Image Credits: Brad Smith and Fred Heberd, The American Chestnut Foundation



Propagation population characterization

- Varietal protection (quality control)
- Parentage analysis / orchard efficiency
 - Pollen contamination
 - Parental contribution to the gene pool
 - Pollen competition
 - Supplemental mass pollination success
 - Mating systems



Pollen contamination

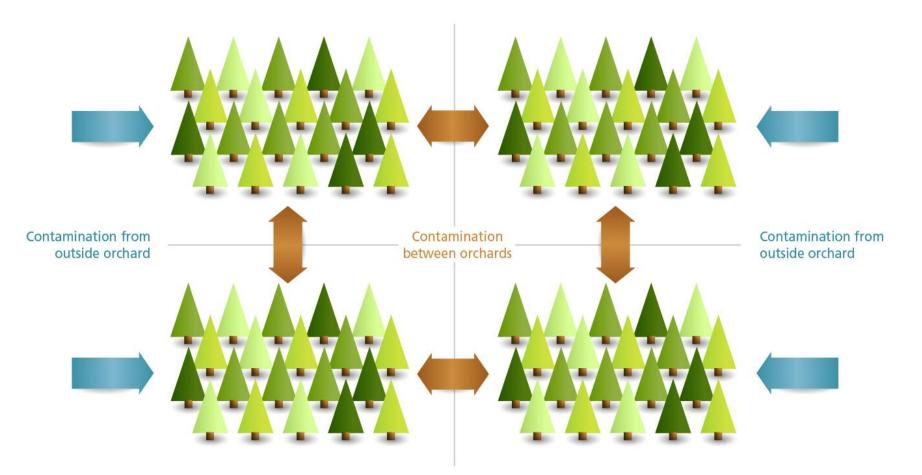


Figure Credit: Nicholas Wheeler, Oregon State University



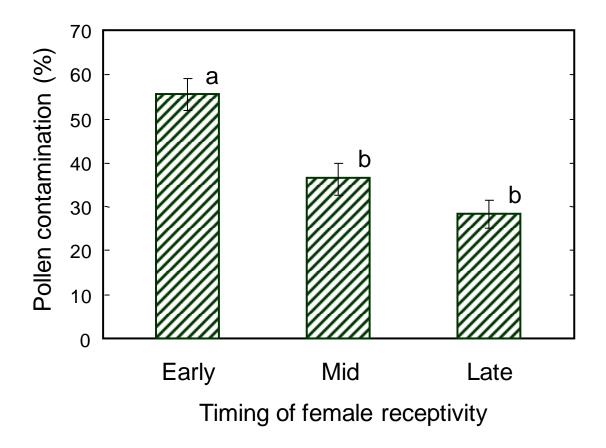
Pollen contamination in DF orchards

Year	Type of seed collection	# of seeds analyzed	Observed seed contamination (%)	Pollen contamination (%) ± SE
1999	Bulk	192 (190 ^ь)	1.0	31.0 ± 3.5
2000	Bulk	192 (102 ^b)	46.9	36.8 ± 5.2
2000	Individual-ramet	240	0	32.0 ± 3.2
2003	Individual-ramet	336	0	41.3 ± 2.8
Mean				35.3 ± 2.4

Slavov et al., 2005; Figure Credit: Glenn Howe, Oregon State

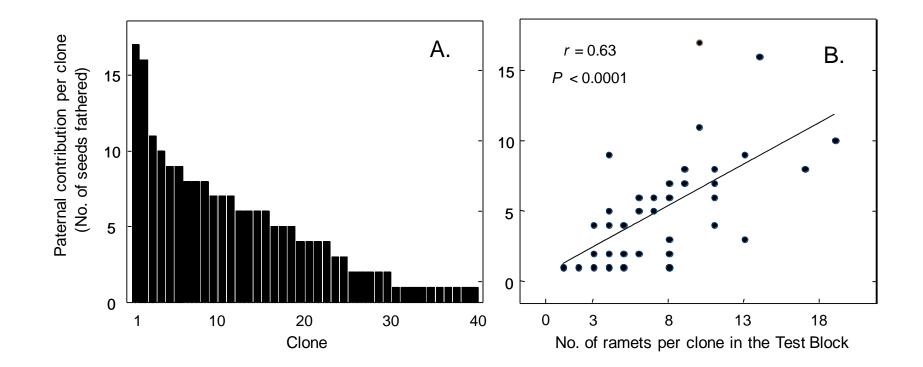


PC is higher in parents that flower early





Differential paternal success





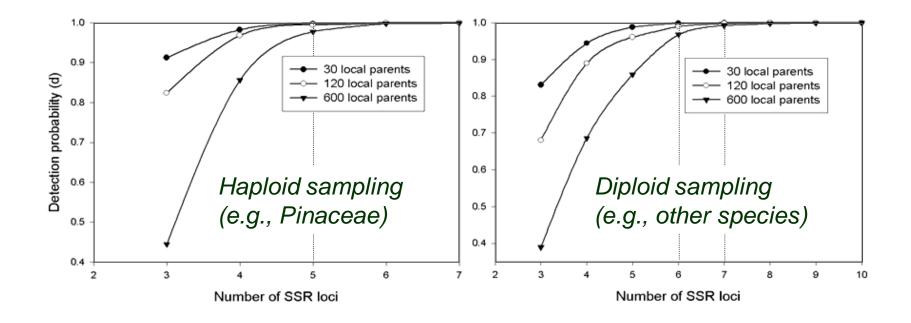
Parentage reconstruction

Table 5. Parent tree identification using SSR genetic markers. The SSR genotypes of two putative open-pollinated (OP) field selections were compared to the genotypes of known progeny growing in genetic test plantations (n = 8-10). If the putative parents in the field are correct, then all of their progeny must have at least one of the two parental alleles. Cases in which a progeny allele matches one of the alleles in the putative parent are shown in white. Allele numbers (e.g., 209 or 216) represent relative lengths of alternative SSR alleles.

	tative OP parent ., tree in the field)			Prog	jeny nu	mber (i								
ID	SSR genotype (marker name)	Progeny allele	1	2	3	4	5	6	7	8	9	10	Inferred genotype of real OP parent	Conclusion: putative parent is:
1	209, 216 (OSU_3F1)	Shorter = Longer =	205 216		202 209		209 219	216 227	216 223		209 211	216 218		Correct
1	184, 191 (OSU_3B9)	Shorter = Longer =	172 191	188 191			176 184	172 191			186 191			Correct
1	254, 256 (OSU_4A7)	Shorter = Longer =		254 284	228 256	256 284	226 256	226 254	254 254		226 254			Correct
2	204, 222 (OSU_3F1)	Shorter = Longer =	210 224	210 214	192 210	210 214	210 226	214 214	190 210	214 220				Incorrect
2	130, 190 (OSU_3B9)	Shorter = Longer =	130 208	188 194	130 210	130 196	188 200		130 188					Incorrect
2	226, 226 (OSU_4A7)	Shorter = Longer =	226 226	226 228	226 244	226 248	226 284	268 284	228 284	282 284			226, 284	Incorrect



Number of loci needed for paternity in DF





Enhanced breeding designs: Informed choices for full-sib matings

- Complementary breeding
 - Identify individuals that differ (genotypes) from one another at a key locus (i.e. R genes for disease resistance)
 - Mate to distribute R genes into other backgrounds
- Pyramiding genes
 - An extension of complementary breeding where you attempt to accumulate desirable alleles at two or more loci into one progeny cohort (see example later)
- Diversity index breeding



Enhanced breeding designs: Using markers for paternity analysis

Polymix breeding with paternity analysis (PMX/WPA)*

- Replace multiple breeding designs (PMX for BV estimation + Fullsib design for advanced generation selection) with just a single PMX test
- Fingerprint the top individuals in the PMX test to determine paternity (maintains pedigree control and manages inbreeding)
- Saves time and cost of full-sib breeding while actually increasing gain potential

* Lambeth, et al., 2001



Tree improvement flow diagram

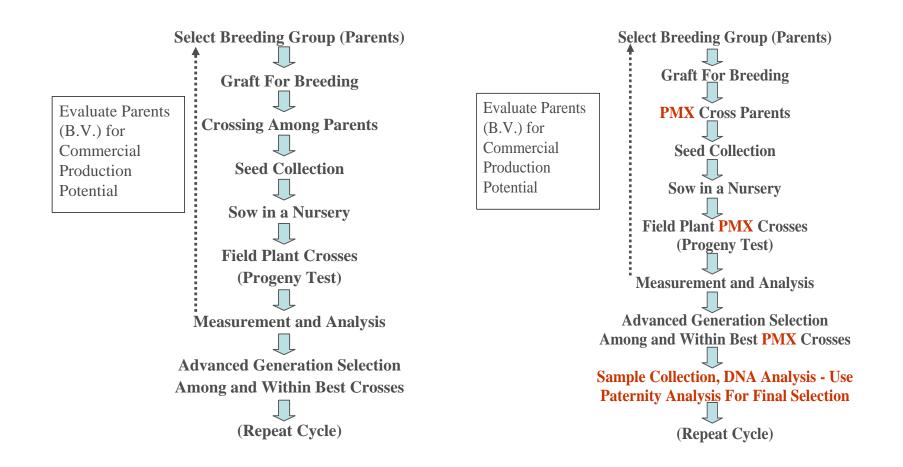


Figure Credit: Clem Lambeth



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Figure Credit: Clem Lambeth



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Figure Credit: Clem Lambeth



Retrospective selection strategy of elite parents based on paternity testing of progeny individuals displaying superior performance using microsatellite markers.

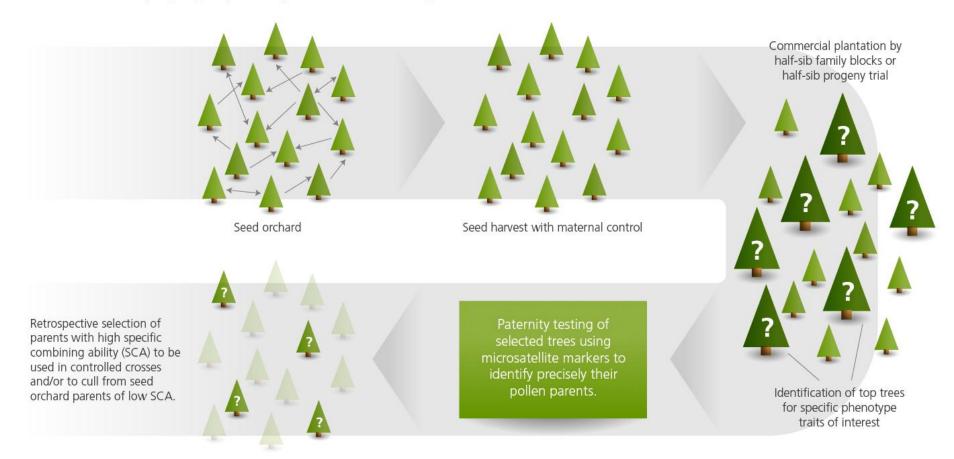


Figure Credit: Modified from Grattapaglia, 2007



Implementation strategies for marker informed breeding in tree improvement

 "All forms of MAS can be applied separately or in conjunction with classical methods of selection (mass, family, within-family, combined and index selection) and can be utilized to make selections for selected, breeding and/or production populations"

- In White, Adams and Neale, Forest Genetics, Chapter 19, Page 554



Approaches to MAS: (Classified by mapping precision)

Classification of three different types of marker-trait associations relevant to *Eucalyptus* MAS (see text for details)

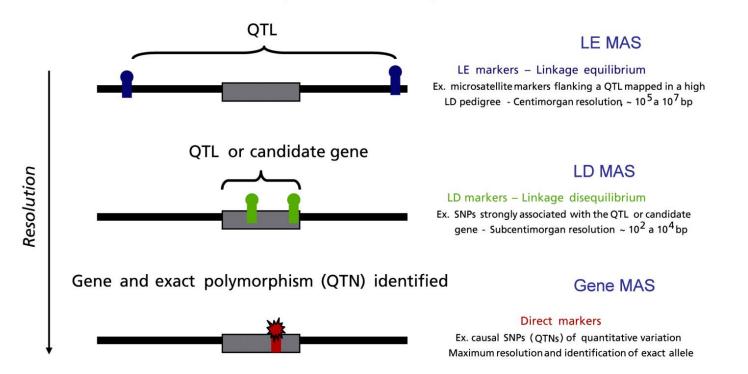


Figure Credit: Modified from Grattapaglia, 2007



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12 Conduct Yearly MIB 2A / MIB 2B MIB 4A / MIB 4B Age 4 Age 4 13 Age 7 Age 7 Select and Graft ML3 Pedigree Cross ML3 14 Age 8 Polymix Cross Polymix Cross Collect Seed & Genotype MIB 6 16 Age 10 Collect Seed Collect Seed & Genotype Collect Seed & Genotype MIB 6 17 Age 11 Collect Seed MIB 3 Pedigree Cross ML4 19 Age 13 Plant PMX Tests Age 1 Age 1 20 Age 15 Age 2 Age 3 Age 3 21 Age 15 Age 4 ML4 MIB 7 22 Age 1 Age 4 ML4 Pedigree Plots Age 1 23 Select and Graft ML4 Pilant Pedigree Plots Age 1 24 Select and Graft ML4 Pilant Pedigree Plots Age 1 25 Select and Graft ML4 Pilant Pedigree Plots Age 1 26 Polymix Cross Polymix Cross Pilant Pedigree Plots Age 1		· ·				10
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www.pinegenome.org/ctgn

Figure Credit: Nicholas Wheeler, Oregon State University.



References cited

- Grattapaglia, D. 2007. Marker–assisted selection in Eucalyptus. p. 251-281. *In*. E. P. Guimaraes, J. Ruane, B. D. Scherf, A. Sonnino, and J. D. Dargie (ed.) Marker assisted selection: Current status and future perspectives in crops, livestock, forestry and fish. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.
- Kubisiak, T. L., F. V. Hebard, C. D. Nelson, J. S. Zhang, R. Bernatzky, H. Huang, S. L. Anagnostakis, and R. L. Doudrick. 1997. Molecular mapping of resistance to blight in an interspecific cross in the genus Castanea. Phytopathology 87: 751-759.
- Lambeth, C., B. C. Lee, D. O'Malley, and N. Wheeler. 2001. Polymix breeding with parental analysis of progeny: an alternative to full-sib breeding and testing. Theoretical and Applied Genetics 103: 930-943.
- Slavov, G. T., G. T. Howe, and W. T. Adams. 2005. Pollen contamination and mating patterns in a Douglas-fir seed orchard as measured by simple sequence repeat markers. Canadian Journal of Forest Research 35:1592-1603. (Available online at: http://dx.doi.org/10.1139/X05-082) (verified 2 June 2011).
- Welz, H. and H. Geiger. 2000. Principles of marker assisted selection I. Qualitative traits. Training manual for a seminar held at IITA, Ibadan, Nigeria, August, 1999. Haussmann, Geiger, Hess, Hash, and Bramel-Cox, Andhra Pradesh, India ICRISAT.
- White, T. L, W. T. Adams, and D. B. Neale. 2007. Forest genetics. CAB International, Oxfordshire, United Kingdom. Available online at: http://bookshop.cabi.org/?page=2633&pid=2043&site=191 (verified 2 June 2011).



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 Forest health initiative. [Online]. Available at: http://foresthealthinitiative.org (verified 2 June 2011).



Thank You.

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