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CONSERVATION OF MICROSATELLITES AMONG TROPICAL TREES (LEGUMINOSAE)¹

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Although microsatellites or simple sequence repeats (SSRs) have become a popular tool in genetic mapping and gene flow studies, their utility is limited due to paucity of information about DNA sequences in plants. We tested the utility of microsatellite markers characterized for the tropical tree *Pithecellobium elegans* as a genetic tool for related species. The results indicate that SSR loci are conserved among closely related species, and SSR primers developed for *P. elegans* could be successfully used as a genetic tool in several species of the tribe Ingeae. This study indicates that there is high potential for the transfer of SSR markers among closely related taxa, circumventing laborious cloning and screening procedures involved in characterizing SSR loci for many species.

Key words: Ingeae; Mimosoideae; phylogeny; *Pithecellobium*; *rbcL*; simple sequence repeat.

In recent years, microsatellites or simple sequence repeats (SSRs) have become a popular tool for genetic mapping (Dietrich et al., 1992; Hearne, Gosh, and Todd, 1992; Weissenbach et al., 1992), and analysis of paternity and gene flow (Amos, Schlotterer, and Tautz, 1993; Chase et al., 1996). This popularity stems from the high allelic diversity found at the SSR loci, the codominance of alleles, and the relatively simple polymerase chain reaction (PCR)-based screening methods. The utility is limited due to the paucity of DNA sequence information for natural populations. Thus costly and laborious cloning and screening procedures limit the number of species that can be studied. In general, SSR markers have been characterized for each species being studied. It is possible that SSR primers developed for one species can be used to detect polymorphism at "homologous" loci of a related species. For several groups of animals, the utility of heterologous primers for the identification of SSRs has been investigated (Schlotterer, Amos, and Tausz, 1991; Fitzsimmons, Moritz, and Moore, 1995; Glenn et al., 1996), but there are few such studies with plant groups. Thomas and Scott (1993) and Saghai-Marouf et al. (1994) characterized SSR variability among grapevine cultivars and a worldwide collection of barley, respectively. Wu and Tanksley (1993) have assessed SSR diversity for accessions of rice and showed that the primers were capable of identifying SSRs in conspecific taxa. Kijas, Fowler, and Thomas, (1995) examined several interfertile cultivars and species of the genera *Citrus* and *Poncirus* and also found that the identification of SSRs from closely related taxa was possible. No study in plant groups has examined the conservation and allelic diversity of SSRs at higher taxonomic scales, nor has any study examined the variability of SSRs within populations of these more distantly related taxa.

Here we examine the extent to which SSR primers

developed for one tropical tree species can be used to amplify SSR loci in other species. We used the primers developed for a tropical rain forest tree, *Pithecellobium elegans*, to detect SSR loci in selected species of the same family (Leguminosae). Because the species differ in the degree of relatedness to *P. elegans*, the tests allow us to assess the correlation between primer homology and genetic relatedness based on chloroplast-encoded *rbcL* gene sequence data.

Specifically, we address the following questions: (1) Can the SSR primers developed for one species be used to amplify SSR markers for related species? (2) Is the cross compatibility of SSR primers correlated with genetic relatedness, and at what taxonomic level are these primers potentially useful? (3) Do related species have similar allelic diversity at a given locus? We also present the phylogenetic tree of selected legume species based on *rbcL* sequence data.

MATERIALS AND METHODS

We selected two to six individuals from 13 species in the Leguminosae, 12 species from the subfamily Mimosoideae, and one species from Papilionoideae (Table 1).

DNA was extracted following a protocol modified from Bernatzky and Tanksley (1986). About 200–300 mg of fresh leaves were placed in a plastic bag (Ziplock brand freezer bags) with 2 mL of ice cold extraction buffer (0.35 mol/L sorbitol, 100 mmol/L Tris pH 7.5, 5 mmol/L EDTA, and 0.02 mol/L sodium bisulfite), and crushed with a roller. The extract was transferred to a microcentrifuge tube and placed on ice. Tubes were centrifuged at 6000 rpm for 5 min to pellet nuclei. The supernatant was discarded and the pellet was resuspended in 300 μ L of extraction buffer and 300 μ L of nuclei lysis buffer (0.2 mol/L Tris [pH 7.5], 0.05 mol/L EDTA, 2 mol/L NaCl, and 2% CTAB [Hexadecyltrimethylammonium bromide]). Sarkosyl (120 μ L of 5%) was added and incubated at 65°C for 15–30 min. Chloroform:isoamyl alcohol (24:1, 600 μ L) was added and inverted to form an emulsion. Tubes were centrifuged at 7000 rpm for 5 min and the upper phase was transferred to a clean microfuge tube containing 600 μ L of isopropanol. The tubes were inverted several times to mix, and then centrifuged at 14000 rpm for 10 min. The pellet was washed with 70% ethanol, dried, and dissolved in 150 μ L of TE (10 mmol/L Tris [pH 7.5], 1 mmol/L EDTA). Five microlitres of the prepared DNA were used for each PCR reaction.

Eight SSR loci were previously characterized for the species *Pithe-*

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TABLE 1. Taxonomy, source (*rbcl* genbank accession number or country from which samples collected), and number of SSR loci amplified (no. SSR) of selected taxa.

Species	Family	Subfamily	Tribe	Source	No. SSR
<i>Pithecellobium elegans</i>	Leguminosae	Mimosoideae	Ingeae	Costa Rica	6
<i>Balizia pedicellaris</i>	Leguminosae	Mimosoideae	Ingeae	Brazil ^a	6
<i>Enterolobium schomburgkii</i>	Leguminosae	Mimosoideae	Ingeae	Brazil ^a	6
<i>Pithecellobium saman</i>	Leguminosae	Mimosoideae	Ingeae	Costa Rica	2
<i>Pithecellobium longifolium</i>	Leguminosae	Mimosoideae	Ingeae	Costa Rica	5
<i>Enterolobium cyclocarpum</i>	Leguminosae	Mimosoideae	Ingeae	Costa Rica	4
<i>Pithecellobium dulce</i>	Leguminosae	Mimosoideae	Ingeae	Costa Rica	6
<i>Albizia caribaea</i>	Leguminosae	Mimosoideae	Ingeae	Costa Rica	5
<i>Parkia pendula</i>	Leguminosae	Mimosoideae	Parkieae	Brazil ^a	0
<i>Pentaclethra macroloba</i>	Leguminosae	Mimosoideae	Parkieae	Costa Rica	0
<i>Acacia collincii</i>	Leguminosae	Mimosoideae	Acaciae	Costa Rica	0
<i>Dinizia excelsa</i>	Leguminosae	Mimosoideae	Mimoseae	Brazil ^a	0
<i>Cercis canadensis</i>	Leguminosae	Caesalpinioideae	Cercideae	Z70163	NA
<i>Cercis siliquastrum</i>	Leguminosae	Caesalpinioideae	Cercideae	Z70164	NA
<i>Gliricidia sapium</i>	Leguminosae	Papilionoideae	Robinieae	Costa Rica	0
<i>Medicago sativa</i>	Leguminosae	Papilionoideae	Trifolieae	Z70173	NA
<i>Pisum sativum</i>	Leguminosae	Papilionoideae	Vicieae	X03853	NA
<i>Polygala cruciata</i>	Polygalaceae			L01945	NA
<i>Securidaca diversifolia</i>	Polygalaceae			L01955	NA
<i>Cupaniopsis anacardioides</i>	Sapindaceae			L13182	NA
<i>Gossypium hirsutum</i>	Malvaceae			X15886	NA

^a Samples collected by Chris Dick, Harvard University Herbaria, Cambridge, MA.

cellobium elegans (Chase, Kesseli, and Bawa, 1996; Chase et al., 1996). Of these, six pairs of primers (Table 2) were used to amplify DNA of related species in this study. After an initial denaturation step at 94°C, five cycles were performed with 94°C denaturation, 55°C annealing, and 72°C extension temperatures, 1 min at each step, followed by 30 cycles at the same temperatures, but with 30 s at each step. Each amplification was performed in a total volume of 15 µL, which consisted of 0.2 mmol/L dNTP, 2.0 mmol/L MgCl₂, 50 mmol/L KCl, 10 mmol/L Tris-HCl (pH 9.0), 0.1% Triton X-100, 2.5 pmol of reverse primer, 2 pmol of forward primer, 0.5 pmol (0.5uCi) of P33 endlabelled forward primer, and 1.5 µL Taq DNA polymerase. Primer end labelling was done with polynucleotide kinase from Epicentre Technology. The labelling mix consisted of 3 µL of 10X PNK buffer, 12.5 µL of H₂O, 1 µL of T4 polynucleotide kinase, 1.5 µL of Gamma P33 labelled ATP, and 12 µL of oligonucleotide primer (30 pmole). The reaction mix was incubated at 37°C for 30 min and then the enzyme was inactivated at 70°C for 5 min. After thermal cycling, 10 µL of stop solution (Xylene cyanol, Bromophenol blue in deionized formamide) was added. The above amplifications were also repeated at a 45°C annealing temperature.

Amplified products were electrophoresed on 6% denaturing gel with 6 mol/L urea and TBE. Electrophoresis was performed on a S2 electrophoretic apparatus (Owl Scientific Inc., Woburn, Massachusetts) for ~4

h at settings of 1750 V, 55 W, or until xylene cyanol marker migrated ~35–40 cm from the origin.

To reconstruct the phylogeny of the taxa being studied, we selected nucleotide sequences of the chloroplast-encoded *rbcl* gene. The *rbcl* gene was amplified using oligonucleotide primers G1F and G1460R, homologous to the *Gossypium rbcl* gene (Dayanandan, 1995). Amplification reactions contained 200 µmol/L each of dATP, dCTP, dGTP, dTTP, 50 mmol/L KCl, 10 mmol/L Tris-HCl (pH 9.0), 0.1% Triton X-100, 10 pmol of each primer, 2 units of Taq DNA Polymerase, and 1.5 mmol/L MgCl₂ in a total volume of 100 µL. Thermal cycling was performed in a PTC100 thermal cycler (MJ Research, Watertown, Massachusetts) at 94°C for 90 s, 40°C for 60 s, and 72°C for 120 s for 40 cycles. Amplified DNA was purified using Wizard PCR purification columns (Promega Corporation, Madison, Wisconsin) and directly sequenced by Sanger dideoxy chain termination method with thermal cycling using ABI prism 377 automated DNA sequencer (Perkin-Elmer, Applied Biosystems, Foster City, California). Thermal cycling was performed at 30 s at 50°C, 60 s at 70°C, and 90 s at 94°C for 30 cycles. Ten internal primers (Dayanandan, 1995), modified from primers designed by Gerard Zurawski (DNAX Institute, Palo Alto, California) were used for sequencing both strands of the *rbcl* gene. Published *rbcl* sequences of *Polygala cruciata* and *Securidaca diversifolia* of Polyga-

TABLE 2. Oligonucleotide primer sequences, repeat pattern, and number of alleles in *P. elegans* for six microsatellite loci^a.

Locus	Primer (5' to 3')	Clone repeat sequence	Number of alleles
<i>Pel1</i>	CGGTGATGCTCAAACCTTCGT CCTTTCCTACCATTTTTGAA	(GA) 4GGAGAA (GA) 3A (GA) 2	1
<i>Pel2</i>	TAACGCAATCAGTTTATCAA CACACTATTATGTTCAAGA	(GT) 15 (GA) 11	5
<i>Pel3</i>	AGAGATGGACTGGAACTTC CCTCCTTAGATTCTTGCT	(TC) 14 (TA) 13	6
<i>Pel5</i>	TCTCTGCACACAGGAACCTTTTGC CCAGAAATAAGGCTCTTTGCACA	(AAAG) 6	5
<i>Pel6</i>	TCTTATACAATTACAAAAGAAAGGTG CCTACCTCTCCTTATATCTACTCTTT	(CT) 12 (CA) 13 (TA) 2 (CA) 9	15
<i>Pel7</i>	TGGGGTAAGTAGAAGAGATTATCG AATATGCCTTCTTTTGTGATTT	(TG) 17	5

^a Data for *Pel1* to *Pel6* are from Chase, Kesseli, and Bawa (1996).

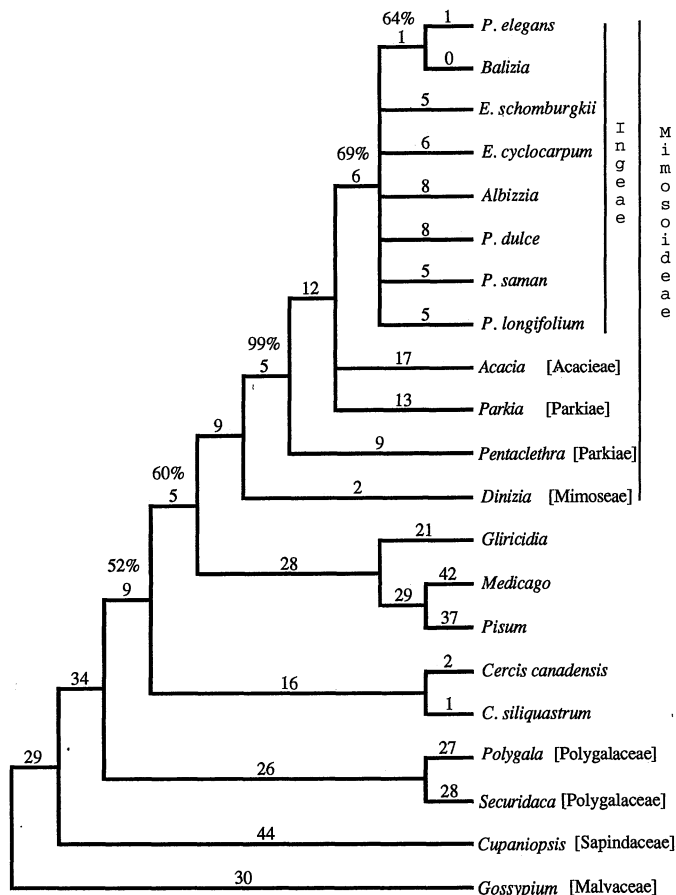


Fig. 1. The strict consensus tree of 73 equally parsimonious trees identified by equally weighted parsimony analysis using *rbcL* sequence data. Length = 514 steps, CI = 0.712, and RI = 0.707. Branch lengths at each node and bootstrap consensus values of branches with <100% are given at each node. Positive amplifications of SSR loci developed from *P. elegans* were observed only among members of the tribe Ingeae.

laceae (Albert, Williams, and Chase, 1992), *Cupaniopsis anacardioides* of Sapindaceae (Chase et al., 1993), *Cercis canadensis*, *Cercis siliquastrum* of Caesalpinioideae (Kaess and Wink, 1995), *Pisum sativum* (Zurawski, Whitfield, and Bottomley, 1986) and *Medicago sativa* (Aldrich et al., 1986) of Papilionoideae, and *Gossypium* (Gulov et al., 1990) of Malvaceae were obtained from the Genbank database.

Sequences were aligned using the ClustalW (Thompson, Higgins, and Gibson, 1994) sequence analysis program. Accuracy of sequences was rechecked by translating to peptide sequence and examining for premature stop codons and frame shifts. Aligned sequences were analyzed using PAUP 3.1.1 (Swofford, 1993) and MacClade 3.04 (Maddison and Maddison, 1993) software packages. Parsimony analysis (Kluge and Farris, 1969) was carried out using the branch and bound algorithm (Hendy and Penny, 1982) in the PAUP package with equally weighted nucleotide transformations and default settings (Swofford and Begle, 1993). The *rbcL* sequence of *Gossypium* (Malvaceae) was used as an outgroup. Robustness of resulting trees was tested by bootstrap analysis (Felsenstein, 1985) of 1000 replicates using the heuristic algorithm in PAUP.

RESULTS

Parsimony analysis with equal character weighting resulted in 73 equally parsimonious trees, each with a

length of 514 steps, a consistency index (CI) of 0.712, and a retention index (RI) of 0.707. The strict consensus tree is given in Fig. 1. *Gossypium* (Malvaceae), *Cupaniopsis* (Sapindaceae), and *Polygala* (Polygalaceae) were used as outgroups. *Cercis canadensis* and *C. siliquastrum* of the subfamily Caesalpinioideae formed a basal clade to remaining legume species. *Gliricidia*, *Medicago*, and *Pisum* of Papilionoideae formed a sister clade to the remaining taxa. *Dinizia* was basal to remaining species of Mimosoideae. *Pentaclethra* formed the next clade. *Parkia*, *Acacia*, and species of the tribe Ingeae formed clades sister to each other. The species of Ingeae formed an unresolved clade. Within this group *P. elegans* and *Balizia* clustered together. Bootstrap analysis was in agreement with the strict consensus tree and most of the branches had 100% bootstrap values except the branches between Polygalaceae and Leguminosae (52%), Caesalpinioideae and remaining species of Leguminosae (60%), *Dinizia* and rest of the mimosoids (99%), *Acacia* and *Parkia* clades and Ingeae (69%), and the clade with *P. elegans* and *Balizia* (65%).

All primers derived from *P. elegans* could amplify SSR fragments in at least seven related species, though the extent of this success varied markedly (Table 3). At 55°C annealing temperature, all primers except for *Pel 6* showed amplification of bands of comparable size to known alleles of *P. elegans*, in as many as seven related species. Decreasing annealing temperature to 45°C resulted in a positive amplification of *Pel 6* as well, with six species (Table 3). Similarly, four species, *Enterolobium schomburgkii*, *Albizia caribaea*, *Pithecellobium dulce*, and *P. longifolium*, which did not show positive amplification products with *Pel 2* at 55°C annealing temperature showed positive amplification at 45°C annealing temperature. *Balizia excelsa* and *E. schomburgkii* showed amplification with all primers tested. *P. longifolium* showed amplification with all but *Pel 6*, whereas *Albizia caribaea* and *P. dulce* showed amplification with all primers except *Pel 1*. *Enterolobium cyclocarpum* showed amplification with *Pel 5*, *Pel 6*, and *Pel 7*, and *P. saman* showed amplification only with *Pel 3* and *Pel 5*. None of the primers tested showed amplification products with DNA from *Gliricidia sepium*, *Dinizia excelsa*, *Acacia collincii*, *Parkia pendula*, and *Pentaclethra macroloba*.

Genetic distances based on divergence of nucleotides in *rbcL* gene from *P. elegans* are given in Table 3. Amplification of SSRs was only observed with species that differ by ten nucleotides or less from the *rbcL* gene of *P. elegans*. No amplification of SSR loci was observed in *Acacia collincii*, *Parkia pendula*, *Dinizia*, *Pentaclethra*, and *Gliricidia*, which showed 21 or more nucleotide position differences from *rbcL* of *P. elegans*. This is also in agreement with the phylogenetic tree obtained through parsimony analysis (Fig. 1) where all species that show positive amplification of SSRs are clustered together.

All loci were polymorphic in at least one other taxon. Considering the narrowness of the germplasm collections for the other species, it was surprising to obtain such high levels of polymorphism. Indeed *Pel 1*, a locus monomorphic in *P. elegans*, showed polymorphism in *Balizia*. The other loci that amplified also showed very high levels of polymorphism. Nearly 60% of the species were polymorphic for any given locus and the average number of

TABLE 3. Amplification of microsatellite loci in different species using SSR primers (Pel) developed from *Pithecellobium elegans* DNA^a. Number of alleles detected in each species for each locus is given. - signifies no amplification products detected; D, number of *rbcL* nucleotide differences as compared to *P. elegans*; AS, number of species that showed amplification for a given locus; PS, number of species that showed polymorphism for a given locus; AL, number of loci that amplified for a given species; PL, number of loci that showed polymorphism for a given species; N, total number of individuals tested for each species.

	D	Pel1	Pel2	Pel2	Pel3	Pel5	Pel6	Pel7	AL	PL	N
Annealing temperature (°C)		55	55	45	55	55	45	55			
Taxon											
<i>Pithecellobium elegans</i> ^a	0	1	5	5	6	5	15	5	6	6	52
<i>Balizia</i>	1	3	3	3	4	2	4	1	6	5	4
<i>Enterolobium schomburgkii</i>	7	1	—	1	1	1	3	1	6	1	4
<i>Pithecellobium saman</i>	7	—	—	—	—	1	—	2	2	1	4
<i>Pithecellobium longifolium</i>	7	1	—	4	3	1	—	2	5	3	4
<i>Enterolobium cyclocarpum</i>	8	—	—	—	—	1	3	2	4	3	4
<i>Pithecellobium dulce</i>	10	1	—	2	6	2	1	1	6	4	6
<i>Albizia caribaea</i>	10	—	—	4	3	2	1	1	5	3	2
<i>Parkia pendula</i>	21	—	—	—	—	—	—	—	0	0	4
<i>Dinizia</i>	24	—	—	—	—	—	—	—	0	0	4
<i>Acacia collincii</i>	25	—	—	—	—	—	—	—	0	0	4
<i>Pentaclethra</i>	27	—	—	—	—	—	—	—	0	0	4
<i>Gliricidia</i>	73	—	—	—	—	—	—	—	0	0	4
Number of species amplified (AS)		4	1	5	5	7	5	7	7	7	
Number of polymorphic species (PS)		1	—	4	4	3	3	3			

^a Data from Chase, Kesseli, and Bawa (1996).

alleles identified per haploid genome scored was 0.29. That is, for every ten haploid genotypes sampled from a given species, on average, we could identify three alleles per locus. This is higher than results obtained in previous studies of populations of *P. elegans* using *Pel2*, *Pel3*, *Pel5*, and *Pel6* (Chase, Kesseli, and Bawa, 1996). Relatively low levels of variability were detected in two species (*P. saman* and *E. schomburgkii*), while high levels were observed in the remaining taxa. These differences could be due to the nature of the collections (possibly from half-sib arrays) or by sampling error.

DISCUSSION

All primers derived from *P. elegans* showed successful amplification of SSR in other taxa, including species from genera other than *Pithecellobium*. Since phylogenetic relationships of many tropical legumes are not well understood and taxonomic treatments are constantly being revised (Polhill and Raven, 1981; Barneby and Grimes, 1996), we have reconstructed the phylogeny of selected species using chloroplast encoded *rbcL* gene sequence data. Although the reconstruction of the phylogeny in this study was not meant for an exhaustive phylogenetic analysis of legumes, but to ascertain the relatedness among taxa as a basis for predicting the utility of SSRs, some enlightening observations regarding species relationships within Leguminosae can be made.

The taxonomic and phylogenetic placement of the Leguminosae as well as phylogenetic relationships within Leguminosae have been a subject of controversy (Cronquist, 1981; Dickison, 1981; Thorne, 1992). Sapindaceae (Thorne, 1992) and Polygalaceae (Chase et al., 1993) are considered to be closely related to Leguminosae. Therefore, we included *rbcL* sequences of both Sapindaceae and Polygalaceae in our analysis and *Gossypium* (Malvaceae) *rbcL* sequence as a distant outgroup. The resulting tree (Fig. 1) is mostly in agreement with the current view on phylogeny of the Leguminosae (Doyle, 1994).

Within Leguminosae, it has been suggested that *Dinizia* may have closer affinity to Caesalpinioideae than to Mimosoideae (M. Nee and R. Barneby, New York Botanical Gardens, personal communication). In our analysis, however, *Dinizia* clusters with Mimosoideae. Caesalpinioideae may be paraphyletic and some taxa, especially the genus *Dimorphandra* of the tribe Caesalpinieae and members of the tribe Casiaea, are considered to be closely related to Mimosoids (Doyle, 1994). Therefore comparative studies using *rbcL* sequence of *Dinizia* with other Caesalpinioideae may be valuable to make any general conclusions on its affinity. Although *Pentaclethra* is considered as a member of the tribe *Parkiae*, *Pentaclethra*, and *Parkia* form a polyphyletic clade, making *Parkiae* an unnatural taxonomic group that warrants further study. While most of the deeper branches of the tree fit well with current views of taxonomic and phylogenetic relationships, the species delineation and relationships at lower level are suspect. *Pithecellobium elegans* seems closer to *Balizia pedicellaris* than to other congeneric species. Interestingly, in a recent taxonomic treatment *Pithecellobium elegans* has been renamed as *Balizia elegans* (Barneby and Grimes, 1996). Although polymorphism in *rbcL* gene is of limited utility in resolving phylogenetic relationships between closely related taxa, our data do suggest that *P. elegans* and *B. pedicellaris* are closely related, and the placement of *P. elegans* within *Balizia* by Barneby and Grimes (1996) is justified. Nucleotide sequence data from a polymorphic gene such as the ITS region of *rDNA* (Baldwin, 1992) may provide further insights into genetic relatedness between *Balizia* and *Pithecellobium*.

Enterolobium spp. and *Albizia* spp. also appear to be closely related to *Pithecellobium*. Some systematists have placed taxa of *Pithecellobium* within the genus *Albizia* (Polhill and Raven, 1981). It has been suggested that *Albizia* and *Enterolobium* are closely related and may have derived from ancestors of *Pithecellobium* (Mesquita,

1990). The present data certainly indicate close affinities among these genera. However, further analyses will be necessary for a greater understanding of the phylogenetic relationships and taxonomic boundaries of species.

Although all primers derived from *P. elegans* could amplify SSR fragments in other species, it appears that primer sites are conserved only among taxa within the tribe Ingeae. Our results about conserved sequences are somewhat similar to observations that have been made with certain animal groups (Moore et al., 1991; Schlotterer, Amos, and Tautz, 1991; Levine et al., 1995). Microsatellite loci developed from bovine DNA have shown higher level of conservation in sheep than in horses but are not conserved in humans (Moore et al., 1991). Likewise, the primers for SSR loci characterized from chicken DNA have been used to amplify SSR loci in turkey (Levine et al., 1995). Fitzsimmons, Moritz, and Moore (1995) reported SSR loci in turtles that are found to be conserved across families and Glenn et al. (1996) reported a similar finding for crocodylian genera. The utility of heterologous primers for the amplification of SSRs has also been shown for closely related conspecific or interfertile taxa of plants. Kijas, Fowler, and Thomas (1995) have shown that two sets of primers derived from a *Citrus* × *Poncirus* hybrid could amplify SSRs in these interfertile genera. Similarly, conservation of primers was shown for closely related species in the rice genus *Oryza* (Wu and Tanksley, 1993).

Our study extends this type of analysis to higher taxonomic levels and is among the first plant study to evaluate the allelic diversity in taxa other than that for which the primers were designed. The true utility of SSR loci across taxa depends on the variability of a given locus. Although our samples have limitations, all species and genera within the tribe Ingeae were polymorphic for at least one of the six loci and most taxa examined were polymorphic for three or more loci. In contrast to Fitzsimmons, Moritz, and Moore (1995), who found that heterozygosity is consistently higher in species from which the primers were designed, we have found that polymorphism levels of certain loci are relatively high in related taxa. A new allele for every diploid genotype scored was found for several species–locus combinations. This variation plus the polymorphism found for previously monomorphic *Pel1* was as good or better than that observed in *P. elegans*.

Different primers show different levels of conservation across taxa and different levels of polymorphisms within these related taxa. Previously we had noted that within *P. elegans*, as others have noted in other species, there is a positive relationship between the length of the repeat and the level of polymorphism; *Pel1* with interrupted short repeats was monomorphic, while *Pel6* with a compound long repeat was highly polymorphic (Chase et al., 1996). We did not observe a negative relationship between the number of alleles identified in the species from which the primers were derived and the number of taxa that could be amplified with those primers as was noted by Glenn et al. (1996) in their study of crocodylian species. Our data show that there is a threshold genetic distance after which no amplification was observed. We do observe a marginal relationship between the CG content of the primer and the ability of the primer to amplify the DNA

of the related taxa. The primers for *Pel5* with the highest CG content (48%) amplified the DNA of all taxa within the tribe Ingeae, while the primers for *Pel2* with the lowest CG ratio (30%) amplified at standard 55°C annealing temperatures the DNA of only one related taxon. Dropping the annealing temperature for this primer pair did elevate to five the number of taxa for which SSRs could be identified.

The data of this study indicate that there is a high potential for the transfer of SSR markers among related taxa. While the conservation of primers for SSR loci was generally limited to the species and genera of the tribe Ingeae, the high variability derived within these species may be unprecedented. If these patterns hold, it is likely that our characterized primers could identify SSRs in hundreds of related species. This utility may vary among major groups, but the potential shown here suggests that considerable time and resources might be saved when primers are available from closely related species. Previously, rapid access to highly polymorphic SSR loci was restricted to species with large DNA databases. The transfer of SSR primers from related species should extend this access and will facilitate the use of SSR loci in a wide variety of genetic analyses related to paternity, mating systems, and gene flow (Terauchi and Konuma, 1994; Chase, Kesseli, and Bawa, 1996; Chase et al., 1996).

LITERATURE CITED

- ALBERT, V. A., S. E. WILLIAMS, AND M. W. CHASE. 1992. Carnivorous plants: phylogeny and structural evolution. *Science* 257: 1491–1495.
- ALDRICH, J., B. CHERNEY, E. MERLIN, AND J. PALMER. 1986. Sequence of the *rbcL* gene for the large subunit of ribulose biphosphate carboxylase-oxygenase from alfalfa. *Nucleic Acids Research* 14: 9535.
- AMOS, B., C. SCHLOTTERER, AND D. TAUTZ. 1993. Social structure of pilot whales revealed by analytical DNA profiling. *Science* 260: 670–672.
- BALDWIN, B. G. 1992. Phylogenetic utility of the internal transcribed spacers of nuclear ribosomal DNA in plants: an example from the Compositae. *Molecular Phylogenetics and Evolution* 1: 3–16.
- BARNEBY, R. C., AND J. W. GRIMES. 1996. Silk tree, guanacaste, monkey's earring: a generic system for the synandrous Mimosaceae of the Americas Part I. *Abarema*, *Albizia*, and allies. *Memoirs of the New York Botanical Garden* 74: 1–292.
- BERNATZKY, R., AND S. TANKSLEY. 1986. Genetics of actin related sequences in tomato. *Theoretical and Applied Genetics* 72: 314–321.
- CHASE, M. R., R. KESSELI, AND K. S. BAWA. 1996. Microsatellite markers for population and conservation genetics of tropical trees. *American Journal of Botany*: 83: 51–57.
- , C. MOLLER, R. KESSELI, AND K. S. BAWA. 1996. Distant gene flow in tropical trees. *Nature* 383: 398–399.
- CHASE, M. W., ET AL. 1993. Phylogenetics of seed plants: an analysis of nucleotide sequences from the plastid gene *rbcL*. *Annals of the Missouri Botanical Garden* 80: 528–580.
- CRONQUIST, A. 1981. An integrated system of classification of flowering plants. Columbia University Press, New York, NY.
- DAYANANDAN, S. 1995. Phylogeny of the tropical tree family Dipterocarpaceae based on nucleotide sequences of the chloroplast *rbcL* gene and morphology. Ph.D. dissertation. Boston University, Boston, MA.
- DICKISON, W. 1981. The evolutionary relationships of the leguminosae. In R. M. Polhill and P. R. Raven [eds.], *Advances in legume systematics*, vols. 1 and 2, 35–54. Royal Botanic Gardens, Kew.
- DIETRICH, W., H. KATZ, S. LINCOLN, H. S. SHIN, J. FRIEDMAN, N. DRACOPOLI, AND E. LANDER. 1992. A genetic map of mouse suitable for typing intraspecific crosses. *Genetics* 131: 423–447.
- DOYLE, J. J. 1994. Phylogeny of the legume family: an approach to

- understanding the origins of nodulation. *Annual Review of Ecology and Systematics* 25: 325–49.
- FELSENSTEIN, J. 1985. Confidence limits on phylogenies: an approach using the bootstrap. *Evolution* 39: 783–791.
- FITZSIMMONS, N. N., C. MORITZ, AND S. S. MOORE. 1995. Conservation and dynamics of microsatellite loci over 300 million years of marine turtle evolution. *Molecular Biology and Evolution* 12: 432–440.
- GLENN, T. C., W. STEPHAN, H. C. DESSAUER, AND M. J. BRAUN. 1996. Allelic diversity in alligator microsatellite loci is negatively correlated with GC content of flanking sequences and evolutionary conservation of PCR amplifiability. *Molecular Biology and Evolution* 13: 1151–1154.
- GULOV, M. K., T. N. ULMASOV, K. A. ALIEV, V. M. ANDRIANOV, AND E. S. PIRUZIAN. 1990. Nucleotide sequence of the chloroplast *rbcL* gene from cotton *Gossypium hirsutum*. *Nucleic Acids Research* 18: 185.
- HEARNE, C., S. GHOSH, AND J. TODD. 1992. Microsatellites for linkage analysis of genetic traits. *Trends in Genetics* 8: 288–294.
- HENDY, M. D., AND D. PENNY. 1982. Branch and bound algorithm to determine minimal evolutionary trees. *Mathematical Biosciences* 59:277–290.
- KAESS, E., AND M. WINK. 1995. Molecular phylogeny of the Papilionoideae (Family Leguminosae): *RbcL* sequences versus chemical taxonomy. *Acta Botanica* 108: 149–162.
- KIJAS, J. M. H., J. C. S. FOWLER, AND M. R. THOMAS. 1995. An evaluation of sequence tagged microsatellite site markers for genetic analysis within *Citrus* and related species. *Genome* 38: 349–355.
- KLUGE, A. G., AND J. S. FARRIS. 1969. Quantitative phyletics and evolution of anurans. *Systematics Zoology* 18: 1–32.
- LEVINE, I., H. H. CHENG, J. C. BACTER, AND J. HILLEL. 1995. Turkey microsatellite DNA loci amplified by chicken specific primers. *Animal Genetics* 26: 107–110.
- MADDISON, W. P., AND D. R. MADDISON. 1993. MacClade: analysis of phylogeny and character evolution. Version 3.04. Sinauer, Sunderland, MA.
- MESQUITA, A. DE L. 1990. Revisao taxonomica do genero *Enterolobium* Mart. (Mimosoideae) para a regio neotropical. Master's thesis. Universidad Federal Rural de Pernambuco, Pernambuco, Brazil.
- MOORE, S. S., L. L. SARGEANT, T. J. KING, J. S. MATICK, M. GEORGES, AND D. J. S. HETZEL. 1991. The conservation of dinucleotide microsatellites among mammalian genomes allows the use of heterologous PCR primer pairs in closely related species. *Genomics* 10: 654–660.
- POLHILL, R. M., AND P. R. RAVEN. 1981. Advances in legume systematics. Royal Botanic Gardens, Kew.
- SAGHAI-MAROOF, M. A., R. M. BIYASHEV, G. P. YANG, Q. ZANG, AND R. W. ALLARD. 1994. Extraordinarily polymorphic microsatellite DNA in barley: species diversity, chromosomal locations, and population dynamics. *Proceedings of National Academy of Sciences, USA* 91: 5466–5470.
- SCHLOTTERER, C., B. AMOS, AND D. TAUTZ. 1991. Conservation of polymorphic simple sequence loci in cetacean species. *Nature* 354: 63–65.
- SWOFFORD, D. L. 1993. PAUP: Phylogenetic analysis using parsimony, version 3.1.1. Illinois Natural History Survey, Champaign IL.
- , AND D. P. BEGLE. 1993. PAUP: Phylogenetic analysis using parsimony. User's manual. Laboratory of Molecular Systematics, Smithsonian Institution, Washington, DC.
- TERAUCHI, R., AND A. KONUMA. 1994. Microsatellite polymorphism in *Dioscorea tokora*, a wild yam species. *Genome* 37: 794–801.
- THOMAS, M. R., AND N. S. SCOTT. 1993. Microsatellite repeats in grapevine reveal DNA polymorphisms when analysed as sequence tagged sites (STSs). *Theoretical and Applied Genetics* 86: 985–990.
- THOMPSON, J. D., D. G. HIGGINS, AND T. J. GIBSON. 1994. CLUSTAL W: improving the sensitivity of progressive multiple sequence alignment through sequence weighting, positions-specific gap penalties and weight matrix choice. *Nucleic Acids Research* 22:46
- THORNE, R. F. 1992. Classification and geography of flowering plants. *Botanical Review* 58: 225–348.
- WEISSENBACH, J., G. GYAPAY, C. DIB, A. VIGNAL, J. MORISSETTE, P. MILLACCEAU, G. VAYSSEIX, AND M. LATHROP. 1992. A second generation linkage map of the human genome. *Nature* 359: 794–801.
- WU, K., AND S. D. TANKSLEY. 1993. Abundance, polymorphism and genetic mapping of microsatellites in rice. *Molecular and General Genetics* 241: 225–235.
- ZURAWSKI, G., P. R. WHITFIELD, AND W. BOTTOMLEY. 1986. Sequence of the gene for the large subunit of ribulose 1,5-bisphosphate carboxylase from pea chloroplasts. *Nucleic Acids Research* 14: 3975.