

Evolution of *Frankia*–Casuarinaceae interactions

Elisabeth Navarro ^a, Carole Rouvier ^b, Philippe Normand ^{b*},
Anne Marie Domenach ^b, Pascal Simonet ^b, Yves Prin ^c

^a Laboratoire de microbiologie, Centre ORSTOM in Nouméa,
BP A5 Nouméa cedex, New Caledonia

^b Laboratoire d'écologie microbienne du sol, UMR CNRS 5557, Université Lyon I,
43, boulevard du 11 novembre 1918, 69622 Villeurbanne cedex, France

^c Laboratoire des symbioses tropicales et méditerranéennes, Campus de Baillarguet,
BP 5035, 34032 Montpellier cedex 1, France

Abstract – Nonisolated *Frankia* strains present in the root nodules of three of the four genera of the Casuarinaceae family (namely, *Casuarina*, *Allocasuarina* and *Gymnostoma*) have been characterised through polymerase chain reaction/restriction fragment length polymorphism (PCR/RFLP) analyses and sequencing of their *nifD*-*nifK* intergenic spacer (IGS). Analyses of the aligned sequences were used to deduce phylogenetic relations of these genes. Strains from *Casuarina* and *Allocasuarina* were found to be in the same cluster, while strains from *Gymnostoma* were closer to Elaeagnaceae strains. The relationships between IGS subgrouping and symbiotic (host spectrum) characteristics of the nonisolated strain confirmed the differences between *Casuarina*/*Allocasuarina* and *Gymnostoma* symbiosis. Genetic diversity among *Casuarina* and *Allocasuarina* microsymbionts seems to be host species-dependent. In contrast, no relation could be found between *Gymnostoma* microsymbionts and host species. The comparison between phylogenetic analyses of the host plants and their microsymbionts suggests that the most coherent evolutionary scenario would be that an early split occurred in the evolution of Casuarinaceae, resulting into two distinct lines of descent. © Inra/Elsevier, Paris

diversity / *Frankia* / Casuarinaceae / coevolution

Résumé – Évolution des interactions *Frankia*–Casuarinaceae. En utilisant des analyses PCR/RFLP et le séquençage de l'intergène *nifD*-K, des souches non isolées de *Frankia* présentes dans les nodosités de trois des quatre genres constituant la famille des Casuarinacées (*Casuarina*, *Allocasuarina* and *Gymnostoma*) ont été caractérisées. L'analyse des séquences alignées a permis d'établir les relations phylogénétiques entre ces souches. Les souches infectives sur *Casuarina* et *Allocasuarina* appartiennent au

* Correspondence and reprints

même groupe phylogénétique, alors que les souches infectives sur *Gymnostoma* sont regroupées avec les souches d'Elaeagnacées. Les relations entre le groupage moléculaire et les caractéristiques symbiotiques du micro-organisme (spectre d'hôte) confirment les différences entre les symbioses impliquant *Casuarina/Allocasuarina* et *Gymnostoma*. La diversité génétique des microsymbiotes de *Casuarina* et *Allocasuarina* semble être corrélée à l'espèce de la plante hôte. Au contraire, aucune relation n'a été trouvée entre le type de microsymbiotes de *Gymnostoma* et l'espèce végétale. La comparaison des arbres phylogénétiques des plantes hôtes et de leurs microsymbiotes suggère qu'une séparation précoce soit survenue dans l'évolution des Casuarinacées, entraînant l'existence de deux lignées de descendants. © Inra/Elsevier, Paris

diversité / *Frankia* / Casuarinacées / coévolution

1. INTRODUCTION

The actinomycete *Frankia* has established a nitrogen-fixing symbiosis with a wide range of dicotyledonous plants. This symbiosis is known to occur in more than 200 species of plants belonging to eight families (Betulaceae, Casuarinaceae, Myricaceae, Elaeagnaceae, Rhamnaceae, Rosaceae, Coriariaceae and Datisceaceae) (Benson and Silvester, 1993).

The Casuarinaceae family is composed of the four genera of tropical dicotyledonous plants *Allocasuarina*, *Casuarina*, *Ceuthostoma* and *Gymnostoma*, of which *Gymnostoma* is considered the most primitive (Johnson and Wilson, 1989). These plants are naturally confined to the Malaysian-Australian Melanesian region but some species, and particularly *Casuarina equisetifolia*, have been exported extensively to other tropical areas worldwide, to be used as windbreaks, to stabilise sand dunes or as a source of fuel wood (Diem et al., 1988; Diem and Dommergues, 1990). This is due in part to the nitrogen-fixing symbiosis that most of the 96 extant species from this family have established with the actinomycete *Frankia* permitting the plants to develop on poor soils.

No study has been carried out on the evolution of *Frankia*-Casuarinaceae relationships. Most of the genetic diversity work on Casuarinaceae infective strains has been done on strains isolated from *Casuarina* spp. and *Allocasuarina* spp. growing in areas where they are not native (Nazaret et al., 1991; Rouvier et al., 1992). Little is known about *Gymnostoma* microsymbionts, the only reports in the literature dealing with three successful isolations of *Frankia* strains in pure culture (Racette and Torrey, 1989; Savauré and Lim, 1991). Therefore, the phylogenetic relationships of *Frankia* strains infective on *Casuarina*, *Allocasuarina* and *Gymnostoma* genera from native areas have not been studied.

With this in mind, we studied the diversity of Casuarinaceae microsymbionts in northeastern Australia and New Caledonia, areas in the natural geographic range of the host plants. Using sequencing and polymerase chain reaction/restriction fragment length polymorphism (PCR/RFLP) analysis, we sought to compare Casuarinaceae microsymbionts and to determine the level of diversity among these strains and their relationships with host plant species.

2. MATERIALS AND METHODS

2.1. Nodules and bacterial strains

Nodules and reference strains used are described in *table 1*.

2.2. DNA extraction from nodules

After peeling off the superficial layers, nodule lobes were disinfected with 30 % w/v H₂O₂ for 5 min, rinsed with sterile distilled water and kept at -20 °C. One nodule lobe was crushed in 500 µL of TCP buffer (100 mM Tris-HCl, pH 8, 1.4 M NaCl, 20 mM EDTA, 2 % w/v CTAB [Sigma, St Louis, MO, USA] and 3 % w/v PVPP [Sigma], pH 8). The mixture was incubated at 65 °C for 1 h and centrifuged at 3 000 *g* for 5 min (20 °C). The supernatant was chloroform-extracted and ethanol-precipitated. The DNA pellet was dissolved in 10 µL of TE buffer (pH 7.5).

2.3. PCR amplification of *nifD-nifK* intergene

For deoxyribonucleic acid (DNA) amplification of a region including the 3' end of *nifD*, the intergenic spacer (IGS), and the beginning of *nifK*, primers FGP807 (5'-CACTGCTACCGGTCGATGAA-3') (Jamann et al., 1993) and FGP333' (5'-CCGGGCGAAGTGGCT-3') (Nalin et al., 1995) were used. PCR amplification was performed in 0.5 mL Eppendorf tubes in a total volume of 50 µL containing: template DNA (approximately 0.1 µg), polymerase reaction buffer (10 mM Tris-HCl, pH 8.3, 1.5 mM MgCl₂, 50 mM KCl, 0.01 % [w/v] gelatine, 20 µM deoxynucleoside triphosphate [dNTP], 1 µM each of the primers and 2.5 units of *TaqI* DNA polymerase [Gibco BRL, Gaithersburg, MD, USA]). DNA amplification was done in a thermocycler (Perkin Elmer, Norwalk, CT, USA) using the following programme: initial denaturation for 3 min at 95 °C, 35 cycles of denaturation (30 s at 95 °C), annealing (30 s at 63 °C) and extension (30 s at 72 °C), and a final extension (2 min at 72 °C). PCR amplification of DNA was checked by agarose gel electrophoresis (2 % w/v) in TBE buffer with 5 µL of PCR product. The gel was stained in an aqueous solution of 1 mg·L⁻¹ ethidium bromide and photographed with HP5 film with a 302-nm ultraviolet source.

2.4. PCR amplification of 16S-23S intergene

Amplifications of a part of the 16S gene and the IGS were performed by using the standard conditions as described previously. Primers FGPS989e (5'-GGGGTCCTTAGGGGCT-3') (Bosco et al., 1992) and FGPL1973' (5'-ATCGGCTCGAGGTGCCAAGGGTC-3') (Navarro et al., 1992) were used for *Gymnostoma* DNA amplifications. Primers FGPS989ac (5'-GGGGTCCGT-AAGGGTC-3') (Bosco et al., 1992) and FGPL132' (5'-CCGGGTTTCCCATT-CGG-3') (Ponsonnet and Nesme, 1994) were used for *Casuarina/Allocasuarina* DNA amplifications.

Table I. Origin of DNA nodules and isolated strains used in this study and 16S-23S IGS-types.

Host plant	Geographical origin ^a	Strain or nodule ^b	IGS-types	Strain reference
<i>Gymnostoma</i> nodules				
<i>G. chamaecyparis</i>	Tontouta (NC)	TC23 - TC24	D	Navarro et al. (1997)
<i>G. chamaecyparis</i>	Tontouta (NC)	TC287	F	This study
<i>G. chamaecyparis</i>	Kouaoua (NC)	KC693	F	This study
<i>G. chamaecyparis</i>	Poum (NC)	PMC753	H	This study
<i>G. deplancheanum</i>	Plaine des Lacs (NC)	PLD170 - PLD185	D	This study
<i>G. deplancheanum</i>	Rivière Bleue (NC)	RBD570	B	This study
<i>G. glaucescens</i>	Mé Aïu (NC)	MG59	D	Navarro et al. (1997)
<i>G. glaucescens</i>	Dzumac (NC)	DG251	D	This study
<i>G. glaucescens</i>	Etoile Filante (NC)	EFG308	E	This study
<i>G. intermedium</i>	Kouaoua (NC)	KI55	C	This study
<i>G. intermedium</i>	Kouaoua (NC)	KI72	C	This study
<i>G. intermedium</i>	Dzumac (NC)	DI247	D	This study
<i>G. intermedium</i>	Dzumac (NC)	DI249	E	This study
<i>G. leucodon</i>	Plum (NC)	PLL300	B	This study
<i>G. leucodon</i>	Rivière des Pirogues (NC)	RPL161	D	Navarro et al. (1997)
<i>G. leucodon</i>	Rivière des Pirogues (NC)	RPL233	C	This study
<i>G. leucodon</i>	Rivière des Pirogues (NC)	RPL526	B	This study
<i>G. nodiflorum</i>	Canala (NC)	CN61	A	Navarro et al. (1997)
<i>G. nodiflorum</i>	Canala (NC)	CN721	B	This study
<i>G. nodiflorum</i>	Tiwaka (NC)	TWN402	A	This study
<i>G. nodiflorum</i>	Nehoue (NC)	NHN750	B	This study
<i>G. nodiflorum</i>	Kouaoua (NC)	KN301	H	This study
<i>G. poissonianum</i>	Kouaoua (NC)	KP54	G	Navarro et al. (1997)
<i>G. poissonianum</i>	Kouaoua (NC)	KP80 - KP81	B	This study
<i>G. poissonianum</i>	Kouaoua (NC)	KP82	D	This study
<i>G. poissonianum</i>	Dzumac (NC)	DP272	D	This study
<i>G. webbianum</i>	Rivière Bleue (NC)	RBW161	B	This study
<i>G. webbianum</i>	Rivière Bleue (NC)	RBW162 - RBW163	D	This study
<i>G. webbianum</i>	Canala (NC)	CW726	B	This study
<i>G. webbianum</i>	Amieu (NC)	AW673	D	This study
<i>G. webbianum</i>	Chagrin (NC)	CHW746	D	This study

Table 1. Continued.

Host plant	Geographical origin ^a	Strain or nodule ^b	IGS-types	Strain reference
<i>Casuarina</i> nodules				
<i>C. equisetifolia/incana</i>	Alva Beach (A)	1Ce1	1	This study
<i>C. equisetifolia</i>	Horseshoe Bay (A)	19Ce1	1	This study
<i>C. equisetifolia</i>	Cow Bay (A)	CeCB	1	Rouvier et al. (1996)
<i>C. equisetifolia</i>	Garners Beach (A)	CeGB	1	Rouvier et al. (1996)
<i>C. equisetifolia</i>	Pallarenda (A)	CePa1	1	Rouvier et al. (1996)
<i>C. equisetifolia</i>	Sauders Beach (A)	CeSB	1	Rouvier et al. (1996)
<i>C. equisetifolia</i>	Wangetti Beach (A)	CeWg2	1	Rouvier et al. (1996)
<i>C. equisetifolia</i>	Wongalinda Beach (A)	CeWB	1	Rouvier et al. (1996)
<i>C. equisetifolia</i>	Cape Hillsborough Beach (A)	14Ce2	2	This study
<i>C. equisetifolia</i>	Wangetti Beach (A)	CeWg1	2	Rouvier et al. (1996)
<i>C. equisetifolia</i>	Mount Low Beach (A)	CeMLB	2	Rouvier et al. (1996)
<i>C. cunninghamiana</i>	Cattle Creek (A)	7Cc1	3	This study
<i>C. cunninghamiana</i>	Bakerville Creek (A)	CcBK	3	Rouvier et al. (1996)
<i>C. cunninghamiana</i>	Herbert River Crossing (A)	CcHRC	3	Rouvier et al. (1996)
<i>C. cunninghamiana</i>	Jourama Falls (A)	CcJF	3	Rouvier et al. (1996)
<i>C. cunninghamiana</i>	Old Chinaman Creek (A)	CcOCC	3	Rouvier et al. (1996)
<i>C. cunninghamiana</i>	Tinaroo Creek (A)	CcTC	3	Rouvier et al. (1996)
<i>C. cunninghamiana</i>	West Watsonville (A)	CcWW	3	Rouvier et al. (1996)
<i>Allocasuarina</i> nodules				
<i>A. torulosa</i>	Paluma Road (A)	37At1	4	This study
<i>A. torulosa</i>	Atherton Rifle Range (A)	AltARR1 - AltARR2	4	Rouvier et al. (1996)
<i>A. torulosa</i>	Bluwater (A)	AltBW	4	Rouvier et al. (1996)
<i>A. torulosa</i>	North of Lawyer Creek (A)	AltNLC	4	Rouvier et al. (1996)
<i>A. littoralis</i>	Eungella Road (A)	11Al1	5	This study
<i>A. littoralis</i>	Atherton (A)	AltAT	5	Rouvier et al. (1996)
<i>A. littoralis</i>	Kuranda (A)	AltKur1 - AltKur2	5	Rouvier et al. (1996)
<i>A. littoralis</i>	West of Herberton (A)	AltWH	5	Rouvier et al. (1996)

Table 1. Continued.

Host plant	Geographical origin ^a	Strain or nodule ^b	IGS-types	Strain reference
<i>Casuarina</i> strains				
<i>C. equisetifolia</i>	Dakar (Senegal)	D11 (atypical) (U)	ND	Gauthier et al. (1981)
<i>C. cunninghamiana</i>	Florida (USA)	Cc13 (9)	1	Zhang et al. (1984)
<i>C. equisetifolia</i>	Senegal	CeD (9)	1	Diem and Dommergues (1983)
<i>Elaeagnaceae</i> strains				
<i>Elaeagnus umbellata</i>	Illinois (USA)	EUN1f (6)	ND	Lalonde et al. (1981)
<i>Hippophaë rhamnoides</i>	Alps (France)	HRN18a (7)	ND	Moiroud and Faure-Reynaud (1983)
<i>E. angustifolia</i>	Ohio (USA)	EaN1-pec (5)	ND	Lalonde et al. (1981)
<i>E. angustifolia</i>	Ecully (France)	Ea1-12 (4)	ND	Fernandez et al. (1989)
<i>Sherpherdia canadensis</i>	Quebec (Canada)	SCN10a (U)	ND	Mort et al. (1983)
<i>Alnus</i> strain				
<i>Alnus rubra</i>	Oregon (USA)	Ar13 (1)	ND	Berry and Torrey (1979)

^a NC: New Caledonia, A: Australia; ^b genomic species numbers are in parentheses; U: undetermined species.

2.5. Sequencing of IGS amplicons

Before sequencing, the amplification reaction mix was purified by using Centricon-30 concentrators (Amicon-Grace Company, Epernon, France). The amplicons were sequenced using the Deaza G/A sequencing kit (Pharmacia Biotech SA, St-Quentin-Yvelines, France) and the direct DNA sequencing method described by Winship (1989). The fragments were sequenced in both directions. The sequences were determined for both strands.

2.6. Data analysis

The sequences were aligned with previously published sequences (Nalin et al., 1995; Navarro et al., 1997) using the multiple-alignment CLUSTA1V algorithm (Higgins and Sharp, 1988), with manual refinements in the noncoding regions. Distances were calculated according to Kimura's two-parameter model (Kimura, 1980) and phylogenetic analyses were made using neighbour-joining (N-J) (Saitou and Nei, 1987) and parsimony methods (Swofford, 1993). A bootstrap confidence analysis was performed with 1 000 replicates to determine the reliability of the distance tree topologies obtained (Felsenstein, 1985). The resulting tree was drawn by using the N-J plot software (Perrière and Gouy, 1996).

2.7. Amplicons restriction analysis

Restriction endonuclease digestions were done with 15 μL of PCR reaction mixture for each reaction. The endonucleases, *NciI*, *MspI*, *HaeIII* (all from Boehringer Mannheim, Meylan, France) and *ScrF1* (Ozyme, Montigny Le Bretonneux, France) were used as specified by the manufacturers. Electrophoresis was carried out in a horizontal slab gel on a 4% (w/v) Nusieve (FMC, Rockland, ME, USA) agarose gel containing 0.5 $\mu\text{g mL}^{-1}$ ethidium bromide, using TBE electrophoresis buffer (89 mM Tris base, 89 mM boric acid, 2 mM EDTA). Gels were run at 4 V cm^{-1} for 3 h and photographed as described previously.

3. RESULTS

3.1. Amplification

The method used for extracting DNA from Casuarinaceae nodule lobes provided endophyte DNA that was pure enough to be efficiently amplified with the sets of primers tested (data not shown). A DNA fragment corresponding to the 16S-23S IGS was obtained for all the 55 templates tested, including DNA from isolates and from nonisolated strains (data not shown).

3.2. Sequencing and comparison of the *nifD*-*nifK* intergenic spacer

By using the sequencing strategy shown in *figure 1*, a sequence that covers the 3' end of *nifD*, the IGS and the beginning of *nifK* was obtained for all 11 DNAs studied and aligned with the published sequences (Nalin et al., 1995; Navarro et al., 1997) (*figure 2*).

	401				500					
Ar13	CCTCGACCAC	AAGCAATCT	TCGCGACGA	GGTCTACCAG	AAGCAATCTG	AGGGCAAGCG	CGAGTTCGAG	AACGGCGGCC	CGAAGGAAGA	GGTCCACCGG
RFL161	CCTCGACCAC	CGAGCTCTT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCGA	TCGACGCCGA	GGTCAACCGG
MG59	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
TC24	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
CN61	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
KP54	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
EUN1f	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
SCN10a	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
HRN18a	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
Ea1-12	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
EaN1-pec	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
D11	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
Ce13	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
Ced	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
1Ce11	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
19Ce1	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
14Ce2	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
7Ce1	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
37At1	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
11Al1	CCTCGACCAC	ACCGAGCTGT	TCRAGGACGA	GGTCTACCAC	AAGCAATCTG	AGACCAAGCG	CGAGTTCGAG	AACGGTGCAG	ATCAGCCCGA	GGTCAACCGG
	501		540	544						
Ar13	GTCTCTGAGT	GGACCCGCGG	GTGGGATAC	CGGGAGAAGA	ACTT					
MG59	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
RFL161	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
TC24	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
CN61	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
KP54	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
EUN1f	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
SCN10a	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
HRN18a	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
Ea1-12	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
EaN1-pec	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
D11	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
Ce13	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
Ced	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
1Ce11	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
19Ce1	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
14Ce2	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
7Ce1	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
37At1	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					
11Al1	GTCTCTGAGT	GGACCCGTFAC	CTGGGATAC	CGCGAGAAGA	ACTT					

Figure 2. (Continued).

In the group of *Casuarina*/*Allocasuarina*-infective strains, up to six differences were observed (corresponding to 0.018 substitutions/site). In the group of Elaeagnaceae-infective strains, between 6 and 71 differences were observed (corresponding to 0.014–0.232 substitutions/site). The *Alnus*-infective strains exhibited between 84 and 175 differences with *Casuarina*-infective strain CcI3 and *Gymnostoma* microsymbiont MG59, respectively.

Two clusters were identified by using the distance matrix (*table II*) and the resulting phylogenetic tree (*figure 3*).

Cluster 1 is a very tight group that contains *Casuarina* and *Allocasuarina* microsymbionts. Two *C. equisetifolia* microsymbionts, 1Ce11 and 19Ce1, have identical sequence with that of the reference *Casuarina* infective strains (*table II*). The remaining *C. equisetifolia* microsymbiont, 14Ce2, is very closely related to the *C. cunninghamiana* microsymbiont. This grouping was also detected by parsimony analysis. *A. torulosa* and *A. littoralis* microsymbionts form a group not confirmed by parsimony analysis. Nevertheless, 37At1 and 11Al1 sequences had a very low level of divergence (*table II*).

The Elaeagnaceae-infective strains form a broad group designated cluster 2. This coherent cluster (100 % of the bootstrap replicates) was also detected by parsimony analysis. The level of sequence divergences was higher in this cluster than in cluster 1. *Gymnostoma* microsymbionts belonged to cluster 2. They form a coherent group (100 % of the bootstrap replicates, parsimony analysis) with EUN1f and SCN10a.

3.3. PCR/RFLP on 16S-23S IGS

Using two restriction enzymes, IGS-types were determined (*table III*; *figure 4*). All reference *Casuarina* and *Allocasuarina* infective strains have

Table II. Distance matrix. Calculated distances (expressed as substitutions/100 sites, below diagonal) as described by Kimura (1980) and observed number of differences between pairs of sequences (above diagonal).

	Ar13	RPL16	MG59	TC24	CN61	KP54	EUN1f	SCN10	HRN18	Ea1	EaN1	D11	Ccl3	CeD	ICei	19Ce1	14Ce2	7Cc1	37At1	11Al1		
Ar13	0	178	175	174	171	147	174	111	105	99	99	119	84	84	84	84	86	87	84	84	84	
RPL161d	573	0	8	7	22	48	25	25	50	58	59	71	60	60	60	60	61	64	61	64	61	62
MG59	563	18	0	6	19	46	24	24	49	54	57	71	61	61	61	61	62	65	62	65	62	63
TC24	552	16	14	0	17	43	22	18	48	55	58	71	57	57	57	57	58	61	58	61	58	59
CN61	548	52	45	40	0	42	18	21	48	56	59	66	59	59	59	59	60	63	60	61	60	61
KP54	487	127	122	113	111	0	46	17	46	55	58	63	58	58	58	58	60	63	59	60	63	60
EUN1f	551	59	56	51	42	121	0	21	44	54	56	68	58	58	58	58	60	63	59	60	63	59
SCN10A	379	70	68	50	59	48	58	0	42	49	50	58	48	48	48	48	50	53	49	50	53	49
HRN18a	392	162	159	155	155	149	141	135	0	37	40	51	46	46	46	46	49	51	47	48	51	47
Ea1-12	358	196	182	185	189	186	180	164	121	0	9	49	35	35	35	35	37	39	36	37	39	36
EaN1-pec	360	201	194	197	201	198	189	169	133	26	0	49	32	32	32	32	34	36	33	34	36	33
D11	431	231	232	230	215	212	219	197	173	168	169	0	50	50	50	50	52	54	53	52	54	53
Ccl3	297	201	206	188	197	194	192	158	153	113	103	170	0	0	0	0	3	5	3	2	5	3
CeD	297	201	206	188	197	194	192	158	153	113	103	170	0	0	0	0	3	5	3	2	5	3
1Cei1	297	201	206	188	197	194	192	158	153	113	103	170	0	0	0	0	3	5	3	2	5	3
19Ce1	297	201	206	188	197	194	192	158	153	113	103	170	0	0	0	0	3	5	3	2	5	3
14Ce2	305	205	210	192	201	202	199	165	164	120	110	178	9	9	9	9	0	4	6	5	4	6
7Cc1	310	216	222	203	213	214	211	176	172	127	117	186	15	15	15	15	12	0	6	5	12	0
37At1	296	204	210	192	201	198	196	161	156	117	106	182	9	9	9	9	18	18	0	1	18	0
11Al1	296	208	214	196	205	202	199	165	160	120	110	178	6	6	6	6	15	15	3	0	15	3

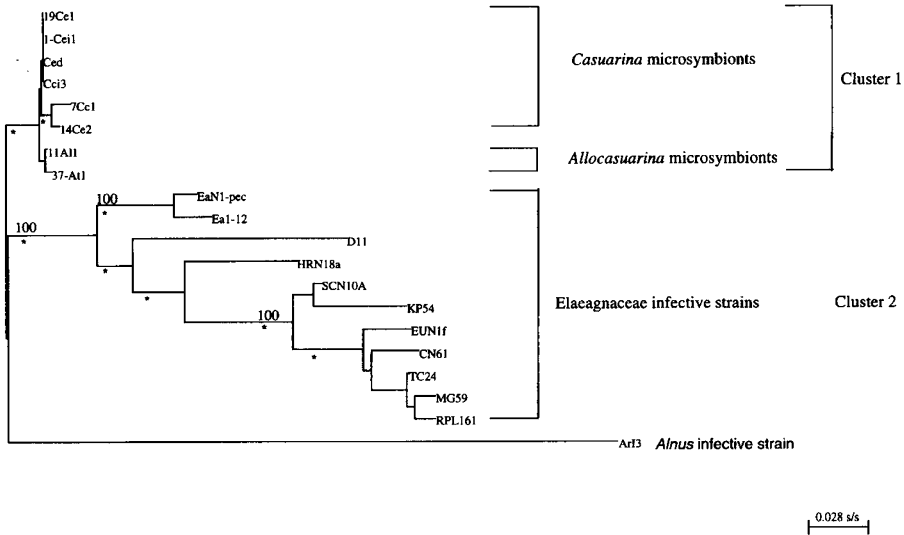


Figure 3. Phylogenetic neighbour-joining tree based on *nifD*-*nifK* intergenic spacer sequences. The bars represent 0.028 substitutions/site. The numbers are the percentages of bootstrap replicates in which the cluster was found. An asterisk indicates that the group was found by parsimony analysis.

Table III. IGS-type determination.

IGS-types	Restriction patterns of the 16S-23S IGS			
	<i>MspI</i>	<i>HaeIII</i>	<i>NciI</i>	<i>ScrF1</i>
A	M1	H1		
B	M1	H2		
C	M2	H1		
D	M2	H3		
E	M3	H3		
F	M3	H4		
G	M4	H1		
H	M5	H5		
1			N1	SF1
2			N2	SF2
3			N3	SF3
4			N1	SF4
5			N4	SF4

similar patterns and were grouped together (IGS-type 1), whereas the *Casuarina*/*Allocasuarina* microsymbionts from Australia are distributed in five IGS-types (table I). *C. equisetifolia* microsymbionts belong to two IGS-types: 1 and 2, the majority being in group 1. IGS-type 3 contains *C. cunninghamiana* microsymbionts. *Allocasuarina* spp. microsymbionts belong to the remaining IGS-types. IGS-type 4 includes *A. torulosa* microsymbionts, whereas IGS-type

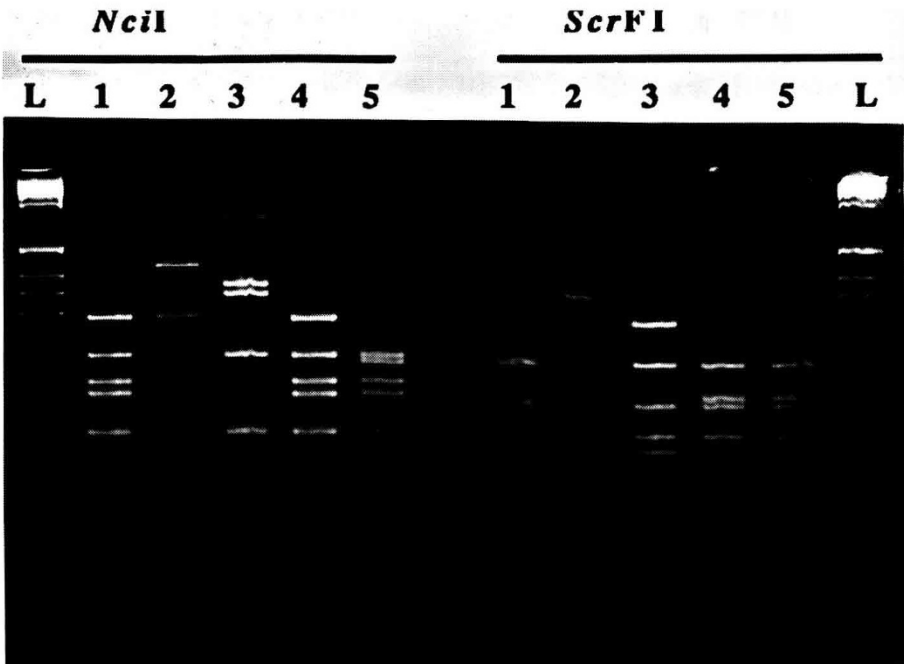


Figure 4. PCR/RFLP patterns of the 16S-23S intergenic spacer (IGS) after digestion with *NciI*, *ScrFI*. Lanes 1 to 5, IGS-types 1 to 5; lane L, 1-kb ladder.

5 includes *A. littoralis* microsymbionts. The genotypic grouping of the *Casuarina* and *Allocasuarina* infective strains was consistently associated with the host plant species (*table IVa*).

The 35 *Gymnostoma* microsymbionts were distributed into eight IGS-types (*table I*). For each *Gymnostoma* species, microsymbionts belong to two or three IGS-types. Conversely, microsymbionts belonging to six IGS-types were associated with several *Gymnostoma* species. IGS-type D is the most promiscuous group, being found with seven of the eight *Gymnostoma* species tested.

The grouping of the strains according to molecular criteria was not related to the grouping based on the host plant species, since each species was found to have established naturally a symbiosis with microsymbionts classified in several IGS- types (*table IVb*).

4. DISCUSSION

Coevolution has been found in several host-pathogen systems (Futuyama, 1986) and in highly specific obligate mutualism such as endosymbiosis (Futuyama, 1986; Moran et al., 1993). Coevolution can be either loose or strict, but this must be confirmed by evidence for the congruence of the two partners' phylogenetic trees.

Comparative studies of the phylogenies of host plant and symbionts constitute a promising approach for the elucidation of the evolution of actinorhizal

Table IV. Distribution of *Frankia* 16S-23S IGS-types as a function of Casuarinaceae species.**IVa.** *Casuarina* and *Allocasuarina* species.

Host plant	IGS-types				
	1	2	3	4	5
<i>C. equisetifolia</i>	+	+			
<i>C. cunninghamiana</i>			+		
<i>A. torulosa</i>				+	
<i>A. littoralis</i>					+

IVb. *Gymnostoma* species.

Host plant	IGS-types							
	A	B	C	D	E	F	G	H
<i>G. chamaecyparis</i>				+		+		+
<i>G. deplancheanum</i>		+		+				
<i>G. glaucescens</i>				+	+			
<i>G. intermedium</i>			+	+	+			
<i>G. leucodon</i>		+	+	+				
<i>G. nodiflorum</i>	+	+		+				+
<i>G. poissonianum</i>		+		+			+	
<i>G. webbianum</i>		+	+	+				

symbiosis. Of the 21 dicotyledonous genera described as actinorhizal (Benson and Silvester, 1993), strains capable of fulfilling Koch's postulates or present as microsymbionts in 11 of these have had their 16S determined and compared (Nick et al., 1992). This analysis has shown that the genus *Frankia* is coherent and that isolated strains infective on *Casuarina* are phylogenetically close to those infective on *Alnus*. Study of the plant phylogeny, on the other hand, has shown that *Casuarina* and the other Casuarinaceae genera *Allocasuarina* and *Gymnostoma* formed a phylogenetically coherent family in the Hammamelidae (Maggia and Bousquet, 1994). It was thus expected that the microsymbionts present in the nodules of these three genera would be phylogenetically close.

The present work on the *nifD-nifK* intergenic spacer has shown that, on the contrary, the nonisolated strains present in *Gymnostoma* nodules and *Casuarina/Allocasuarina* nodules belonged to different clusters. *Casuarina/Allocasuarina* microsymbionts form a tight group with a very low level of sequence divergence (figure 3; table II). The phylogenetic tree outlined in this cluster is similar to the trees obtained by PCR/RFLP analysis (figure 5). *Gymnostoma* microsymbionts were in the cluster of Elaeagnaceae-infective strains. Cross-inoculation studies have confirmed that *Gymnostoma*-infective strains are *Elaeagnus*-infective and not *Casuarina*-infective (Navarro et al., 1997).

Differences between *Casuarina/Allocasuarina* and *Gymnostoma* microsymbionts were confirmed by PCR/RFLP analysis of the 16S-23S intergenic spacer (table IV). Genetic diversity among *Casuarina* and *Allocasuarina* microsymbionts

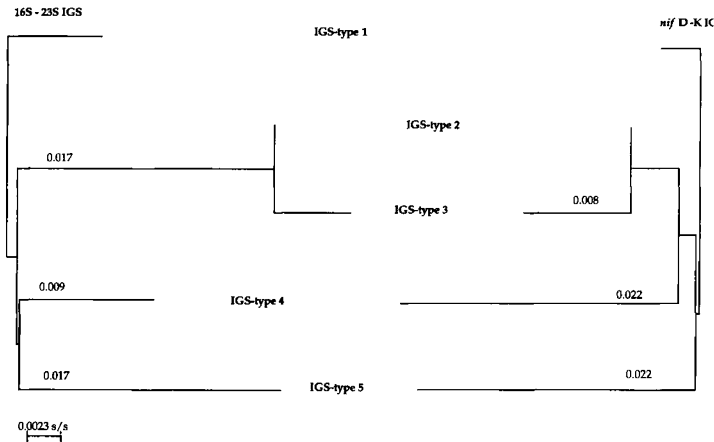


Figure 5. Dendrogram of genotypic relationship of intergenic spacer (IGS) sequences derived by PCR/RFLP analysis according to Rouvier (1995).

bionts seems to be host-species dependent. Cross-inoculation studies support this finding (Reddell and Bowen, 1985; Sellstedt, 1995). This differentiates this group from *Gymnostoma* microsymbionts for which no relation between genetic diversity and host species was observed. Identical results were obtained by cross-inoculation studies (Gauthier, personal communication).

These results mean that in the Casuarinaceae line of descent the host plants did not evolve gradually as proposed by Maggia and Bousquet (1994). These authors suggested that evolution of the symbiosis had been from a promiscuous ancestor identified as comparable to present-day *Gymnostoma* to the very restrictive descendant (*Allocasuarina*) with *Casuarina* in between. Instead, the most coherent scenario would be that an early split occurred in the evolution of Casuarinaceae, resulting in two distinct lines of descent. In each of them evolution of the symbiosis has occurred in two different ways. Evolution of the *Casuarina/Allocasuarina* symbiosis has proceeded towards a greater specificity and specialisation, and is presumably an example of coevolution. These host plants are in symbiosis with hard-to-isolate and slow-growing *Frankia* strains, suggesting that this symbiosis is becoming obligate. More saprophytic *Frankia* strains (Nalin et al., 1997), faster growing and easier to isolate, have established a nonspecific symbiotic association with *Gymnostoma*. No evolutionary relationships could be evidenced in this interaction. These hypotheses could be confirmed by comparing the phylogeny of the two symbiotic partners, using sequencing of host plant and microorganism DNA from the same nodule, from a larger sample of Casuarinaceae species.

ACKNOWLEDGEMENTS

Thanks are expressed to J. Briolay (Centre d'analyse moléculaire de la biodiversité) for technical assistance.

REFERENCES

- Benson D.R., Silvester W.B., Biology of *Frankia* strains, Actinomycete symbionts of Actinorhizal plants, *Microbiol. Rev.* 57 (1993) 293-319.
- Berry A.M., Torrey J.G., Isolation and characterization *in vivo* and *in vitro* of an actinomycetous endophyte from *Alnus rubra* Bong, in: Gordon J.C., Wheeler C.T., Perry D.A. (Eds.), Symbiotic Nitrogen Fixation in the Management of Temperate Forests, Oregon State University, Corvallis, OR, 1979, pp. 69-83.
- Bosco M., Fernandez M.P., Simonet P., Materassi R., Normand P., Evidence that some *Frankia* sp. strains are able to cross boundaries between *Alnus* and *Elaeagnus* host specificity groups, *Appl. Environ. Microb.* 58 (1992) 1569-1576.
- Diem H.G., Dommergues Y., The isolation of *Frankia* from nodules of *Casuarina*, *Can. J. Bot.* 61 (1983) 2822-2825.
- Diem H.G., Dommergues Y., Current and potential uses and management of Casuarinaceae in the tropics and subtropics, in: Schwintzer C.R., Tedpkema J.D. (Eds.), *The Biology of Frankia and Actinorhizal Plants*, Academic Press, Inc., New York, 1990, pp. 317-342.
- Diem H.G., Duhoux E., Simonet P., Dommergues Y., Actinorhizal symbiosis biotechnology: the present and the future, in: Durand G., Bodichon L., Florent J. (Eds.), *Proceedings of the 8th International Biotechnology Symposium, Société française de microbiologie*, Paris, 1988, pp. 984-995.
- Felsenstein J., Confidence limits on phylogenies: an approach using the bootstrap, *Evolution* 39 (1985) 783-791.
- Fernandez M.P., Meugnier H., Grimont P.A.D., Bardin R., Deoxyribonucleic acid relatedness among members of the genus *Frankia*, *Int. J. Syst. Bacteriol.* 39 (1989) 424-429.
- Futuyama D.J., The evolution of interactions among species, in: Davis A., Vesely J. (Eds.), *Evolutionary Biology*, Sinauer Associates, Inc., Sunderland, MA, 1986, pp. 482-504.
- Gauthier D., Diem H.G., Dommergues Y., Infectivité et effectivité des souches de *Frankia* isolées de nodules de *Casuarina equisetifolia* et *Hippophae rhamnoides*, *C.R. Acad. Sci.* 293 (1981) 489-491.
- Higgins D.G., Sharp P.M., CLUSTAL: a package for performing multiple sequence alignments on a microcomputer, *Gene* 73 (1998) 237-244.
- Jamann S., Fernandez M.P., Normand P., Typing method for N₂-fixing bacteria based on PCR-RFLP - application to the characterisation of *Frankia* strains, *Mol. Ecol.* 2 (1993) 17-26.
- Johnson L.A.S., Wilson K.L., Casuarinaceae: a synopsis, in: Crane P.R., Blackmore S. (Eds.), *Evaluation, Systematics and Fossil History of the Hamamelidae*, vol. 2: Higher Hamamelidae, Systematics Association, Clarendon Press, London, special vol. 40B, 1989, pp. 67-188.
- Kimura M., A simple method for estimating evolutionary rates of base substitutions through comparative studies of nucleotide sequences, *J. Mol. Evol.* 16 (1980) 111-120.
- Lalonde M., Calvert H.E., Pine S., Isolation and use of *Frankia* strains in actinorhizae formation, in: Gibson A.H., Newton W.E. (Eds.), *Current Perspectives in Nitrogen Fixation*, Australian Academy of Science, Canberra, 1981, pp. 296-299.
- Maggia L., Bousquet J., Molecular phylogeny of the actinorhizal Hamamelidae and relationships with host promiscuity towards *Frankia*, *Mol. Ecol.* 3 (1994) 459-467.
- Moiroud A., Faure-Reynaud M., Influences de quelques herbicides à large spectre sur la croissance et l'infectivité de cultures pures de *Frankia*, *Plant Soil* 74 (1983) 133-136.

Moran N.A., Muson M.A., Baumann P., Ishikawa H.I., A molecular clock in endosymbiotic bacteria is calibrated using the insect hosts, *Proc. R. Soc. Lond. [Biol.]* 253 (1993) 167–171.

Mort A., Normand P., Lalonde M., 2-O-methyl-D-mannose, a key sugar in the taxonomy of *Frankia*, *Can. J. Microbiol.* 29 (1983) 993–1002.

Nalin R., Normand P., Domenach A.-M., Characterization of a *Frankia* community in a soil column, *Physiol. Plant.* 99 (1997) 732–738.

Nalin R., Domenach A.-M., Normand P., Characterization of an intergenic spacer between *nifD* and *nifK* in *Frankia*, *Mol. Ecol.* 4 (1995) 483–491.

Navarro E., Simonet P., Normand P., Bardin R., Characterization of natural population of *Nitrobacter* spp. using PCR/RFLP analysis of the ribosomal intergenic spacer, *Arch. Microbiol.* 157 (1992) 107–115.

Navarro E., Nalin R., Gauthier D., Normand P., The nodular microsymbionts of *Gymnostoma* spp. are *Elaeagnus*-infective strains, *Appl. Environ. Microb.* 63 (1997) 1610–1616.

Nazaret S., Cournoyer B., Normand P., Simonet P., Phylogenetic relationships among *Frankia* genomic species determined by use of amplified 16S rDNA sequences, *J. Bacteriol.* 173 (1991) 4072–4078.

Nick G., Paget E., Simonet P., Moiroud A., Normand P., The nodular endophytes of *Coriaria* spp. form a distinct lineage within the genus *Frankia*, *Mol. Ecol.* 1 (1992) 175–181.

Perrière G., Gouy M., WWW-Query: an on-line retrieval system for biological sequence banks, *Biochimie* 78 (1996) 364–369.

Ponsonnet C., Nesme X., Identification of *Agrobacterium* strains by PCR-RFLP analysis of pTi and chromosomal regions, *Arch. Microbiol.* 161 (1994) 300–309.

Racette S., Torrey J.G., The isolation, culture and infectivity of a *Frankia* strain from *Gymnostoma papuanum* (Casuarinaceae), *Plant Soil* 118 (1989) 165–170.

Reddell P., Bowen G.D., Do single nodules of Casuarinaceae contain more than one *Frankia* strain? *Plant Soil* 88 (1985) 275–279.

Rouvier C., Caractérisation génétique de *Frankia* nodulant les Casuarinacées : influence de la plante-hôte et de sa zone d'origine, l'Australie, thesis, Université Lyon I, France, 1995.

Rouvier C., Nazaret S., Fernandez M.P., Picard B., Simonet P., Normand P., *rrn* and *nif* intergenic spacers and isoenzyme patterns as tools to characterize *Casuarina*-infective *Frankia* strains, *Acta Oecol.* 13 (1992) 487–495.

Rouvier C., Prin Y., Reddell P., Normand P., Simonet P., Genetic diversity among *Frankia* strains nodulating members of the family Casuarinaceae in Australia revealed by PCR and restriction fragment length polymorphism analysis with crushed root nodules, *Appl. Environ. Microb.* 62 (1996) 979–985.

Saitou R.R., Nei M., A Neighbor-Joining method: a new method for reconstructing phylogenetic trees, *Mol. Biol. Evol.* 44 (1987) 406–425.

Savouré A., Lim G., Characterization of an infective *Frankia* (ISU 0224887) isolated from nodules of *Gymnostoma sumatranum*, *Plant Soil* 131 (1991) 21–27.

Sellstedt A., Specificity and effectivity in nodulation by *Frankia* on southern hemisphere actinorhiza, *FEMS Microbiol. Lett.* 125 (1995) 231–236.

Swofford D.L., PAUP - phylogenetic analysis using parsimony, version 3.1, Illinois Natural History Survey, Champaign, IL, 1993.

Winship P.R., An improved method for directly sequencing PCR amplified material using dimethyl sulfoxide, *Nucleic Acids Res.* 17 (1989) 1266.

Zhang Z., Lopez M.F., Torrey J.G., A comparison of cultural characteristics and infectivity of *Frankia* isolates from root nodules of *Casuarina* species, *Plant Soil* 78 (1984) 79–90.