



Phytophythium: molecular phylogeny and systematics

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Key words

COI
LSU
Oomycetes
Oomycota
Peronosporales
Phytophythium
Pythiales
SSU

Abstract The genus *Phytophythium* (*Peronosporales*) has been described, but a complete circumscription has not yet been presented. In the present paper we provide molecular-based evidence that members of *Pythium* clade K as described by Lévesque & de Cock (2004) belong to *Phytophythium*. Maximum likelihood and Bayesian phylogenetic analysis of the nuclear ribosomal DNA (LSU and SSU) and mitochondrial DNA cytochrome oxidase subunit 1 (COI) as well as statistical analyses of pairwise distances strongly support the status of *Phytophythium* as a separate phylogenetic entity. *Phytophythium* is morphologically intermediate between the genera *Phytophthora* and *Pythium*. It is unique in having papillate, internally proliferating sporangia and cylindrical or lobate antheridia. The formal transfer of clade K species to *Phytophythium* and a comparison with morphologically similar species of the genera *Pythium* and *Phytophthora* is presented. A new species is described, *Phytophythium mirpurensis*.

Article info Received: 28 January 2014; Accepted: 27 September 2014; Published: 30 October 2014.

INTRODUCTION

The genus *Pythium* as defined by Pringsheim in 1858 was divided by Lévesque & de Cock (2004) into 11 clades based on molecular systematic analyses. These clades are generally well supported by morphological features. In particular, *Pythium* species belonging to clade K were observed to be phylogenetically distinct from the rest of the *Pythium* spp. and showed combined features of both *Pythium* and *Phytophthora*. The unique phylogenetic placement of species belonging to clade K has been recognised since the beginning of sequence-based phylogenetics. Briard et al. (1995) and Cooke et al. (2000) showed that *Pythium vexans* was clearly different from other *Pythium* spp. and *Phytophthora* using the ribosomal large subunit (LSU) and internal transcribed spacer (ITS), respectively. In a multi-gene study, Villa et al. (2006) showed that *Pythium* species belonging to clade K were closely related to *Phytophthora*. The uniqueness of this clade was also supported by Bedard et al. (2006) by analysis of the organisation of the 5S gene family. In species in clade K, the 5S rRNA genes were predominantly linked to the rDNA repeat mostly in tandem arrays in the same orientation as the rRNA genes.

Phytophythium is a new genus in the family *Pythiaceae*, order *Peronosporales* that was described with *Phytophythium sindhum* as the type species by Bala et al. (2010b). They showed that *Phytophythium sindhum* is a member of clade K. Uzuhashi et al. (2010) divided *Pythium* into five new genera and assigned the name *Ovatisporangium* to the members of clade K, this name, however, is a later synonym of *Phytophythium*. *Phytophythium* therefore has priority. The objective of the present study is to

establish which species belong to clade K and to make new taxonomic combinations for these species. To achieve this goal, phylogenies based on nuclear LSU rRNA (28S), SSU rRNA (18S) and mitochondrial DNA cytochrome oxidase 1 (COI) as well as statistical analyses of the pairwise distances from these datasets were prepared with an extensive coverage of the oomycetes containing almost all *Pythium* and *Phytophthora* species available in culture. The ITS gene region was also used to ascertain the position of all possible species in clade K but not for phylogeny since it is too variable to align sequences between *Pythium* and *Phytophthora*. Diagnostic morphological features of the group are also presented and discussed.

MATERIALS AND METHODS

Morphological studies

The strains used for the phylogenetic study were morphologically examined to verify their identity and to find the characteristic features of the group. The methods used for cultivation of the strains for study of morphology and zoospore development are the same as described by de Cock & Lévesque (2004).

DNA extraction, amplification and sequencing

Almost 300 strains of *Pythium*, *Phytophythium*, *Phytophthora*, *Halophytophthora* and *Albugo* were used in this study (Table 1). DNA was extracted using the protocols as described in Bala et al. (2010a). PCR amplifications for the rDNA LSU and ITS1-5.8S-ITS2 regions and mitochondrial DNA COI were done using the protocols and primer sequences as provided in Robideau et al. (2011). The SSU region was amplified using forward primer NS1 (5'-TAGTCATATGCTTGTCTC-3') (White et al. 1990) and reverse primer OomLo5.8S47B (3'-CGCATTACG-TATCGCAGTTCGAG-5') (Mazzola et al. 2002), with an initial denaturation at 95 °C for 3 min, 35 cycles of denaturation at 95 °C for 30 s, primer annealing at 55 °C for 45 s, elongation at 72 °C for 2 min and final elongation at 72 °C for 8 min. Sequencing primers used for the SSU region were NS1, NS2 (5'-GGCT-GCTGGCACCAGACTTGC3'), NS3 (5'-GCAAGTCTGGTGC-CAGCAGCC), NS4 (5'-CTTCCGTC AATTCCTTTAAG3'), NS5

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Table 1 Species and isolates included in the study, showing GenBank accession numbers for each gene.

Species	Strain Number	Clade	GenBank Accessions					
			SSU ITS_28S	SSU ITS	SSU	COI	LSU	ITS
<i>Albugo candida</i>	AC2V		–	–	–	HQ708184	HQ665049	–
	AC7A		–	–	HQ643110	HQ708183	HQ665050	–
	ACCS		–	–	KF853245	–	–	–
<i>Halophytophthora avicenniae</i>	CBS188.85	Halophytophthora	–	–	–	HQ708219	HQ665146	–
<i>Halophytophthora operculata</i>	CBS241.83	Phytophythium	–	–	GU994173	KF853238	KJ128038	KJ128038
<i>Halophytophthora polymorphica</i>	CBS680.84	Halophytophthora	–	–	–	–	HQ665288	–
<i>Phytophthora alni</i>	P10564	Clade 7	–	–	JN635200	–	–	–
<i>Phytophthora alticola</i>	P16053	Clade 4	–	–	JN635264	–	–	–
<i>Phytophthora andina</i>	P13660	Clade 1	–	–	JN635253	–	–	–
<i>Phytophthora arecae</i>	CBS305.62	Clade 4	–	–	–	HQ708218	HQ665200	–
<i>Phytophthora austrocedrae</i>	P16040	Clade 8	–	–	JN635271	–	–	–
<i>Phytophthora batemanensis</i>	CBS679.84	Halophytophthora	–	–	–	HQ708220	HQ665286	–
<i>Phytophthora bisheria</i>	P10117	Clade 2	–	–	–	–	EU080746	–
	P11311	Clade 2	–	–	JN635246	HQ261249	–	–
	CBS291.29	Clade 10	–	–	–	HQ708221	HQ665190	–
<i>Phytophthora boehmeriae</i>	P1257	Clade 10	–	–	JN635228	–	–	–
	P6950	Clade 10	–	–	–	–	EU080166	–
	P1044	Clade 2	–	–	JN635168	–	–	–
<i>Phytophthora botryosa</i>	CBS178.87	Clade 8	–	–	–	HQ708225	HQ665144	–
<i>Phytophthora brassicae</i>	P10155	Clade 8	–	–	JN635172	–	–	–
	P3273	Clade 8	–	–	JN635066	–	–	–
	CBS108.09	Clade 1	–	–	–	KJ128035	KJ128036	–
<i>Phytophthora cactorum</i>	P0714	Clade 1	–	–	JN635210	–	–	–
	P10365	Clade 1	–	–	JN635194	–	–	–
	CBS554.88	Clade 2	–	–	–	HQ708250	HQ665266	–
<i>Phytophthora capsici</i>	P6522	Clade 2	–	–	JN635061	–	–	–
	P10719	Clade 9	–	–	JN635227	–	–	–
<i>Phytophthora captiosa</i>	P10720	Clade 9	–	–	JN635229	–	–	–
	CBS144.22	Clade 7	–	–	–	HQ708257	HQ665126	–
<i>Phytophthora cinnamomi</i> var. <i>parvispora</i>	CBS411.96	Clade 7	–	–	–	HQ708268	HQ665231	–
<i>Phytophthora cinnamomi</i> var. <i>robiniae</i>	P16351	Clade 7	–	–	JN635269	–	–	–
<i>Phytophthora citricola</i>	CBS221.88	Clade 2	–	–	–	HQ708269	HQ665161	–
<i>Phytophthora citrophthora</i>	CBS950.87	Clade 2	–	–	–	HQ708272	HQ665305	–
	P1212	Clade 2	–	–	JN635223	–	–	–
	P3942	Clade 1	–	–	JN635111	–	–	–
<i>Phytophthora clandestina</i>	P6102	Clade 2	–	–	JN635058	–	–	–
<i>Phytophthora colocasiae</i>	P16165	Clade 8	–	–	JN635259	–	–	–
<i>Phytophthora drechsleri</i>	CBS468.81	Clade 8	–	–	–	HQ708276	HQ665238	–
	P10331	Clade 8	–	–	–	–	EU079511	–
	P1087	Clade 8	–	–	–	HQ261299	–	–
<i>Phytophthora erythroseptica</i>	P1087	Clade 8	–	–	JN635260	–	–	–
	CBS129.23	Clade 8	–	–	–	HQ708286	HQ665121	–
	P1693	Clade 8	–	–	JN635249	–	–	–
<i>Phytophthora europaea</i>	P10324	Clade 7	–	–	JN635189	–	–	–
<i>Phytophthora fallax</i>	P10722	Clade 9	–	–	JN635219	–	–	–
<i>Phytophthora foliorum</i>	P10969	Clade 8	–	–	–	HQ261307	EU079704	–
<i>Phytophthora fragariae</i>	CBS209.46	Clade 7	–	–	–	HQ708294	HQ665150	–
	P1435	Clade 7	–	–	JN635233	–	–	–
<i>Phytophthora frigida</i>	P16051	Clade 2	–	–	JN635162	–	–	–
<i>Phytophthora gonapodyides</i>	CBS363.79	Clade 6	–	–	–	–	HQ665216	–
	CBS554.67	Clade 6	–	–	–	HQ708297	HQ665265	–
	P10337	Clade 6	–	–	JN635201	–	–	–
	P3700	Clade 6	–	–	JN635141	–	–	–
<i>Phytophthora hedraiaandra</i>	CBS118732	Clade 1	–	–	–	HQ708300	–	–
	PDA331	Clade 1	–	–	–	–	EU080880	–
<i>Phytophthora heveae</i>	CBS296.29	Clade 5	–	–	–	HQ708301	HQ665194	–
	P10167	Clade 5	–	–	JN635090	–	–	–
<i>Phytophthora hibernalis</i>	P3822	Clade 8	–	–	JN635091	–	–	–
<i>Phytophthora himalayensis</i>	CBS357.59	Clade 8	–	–	–	–	HQ665215	–
<i>Phytophthora humicola</i>	CBS200.81	Clade 6	–	–	–	–	HQ665148	–
	P3826	Clade 6	–	–	JN635108	–	–	–
<i>Phytophthora idaei</i>	P6767	Clade 1	–	–	JN635116	–	–	–
<i>Phytophthora ilicis</i>	P3939	Clade 3	–	–	JN635092	–	–	–
<i>Phytophthora infestans</i>	CBS366.51	Clade 1	–	–	–	HQ708309	HQ665217	HQ643247
<i>Phytophthora insolita</i>	P6703	Clade 9	–	–	JN635140	–	–	–
<i>Phytophthora inundata</i>	CBS215.85	Clade 6	–	–	–	HQ708311	HQ665154	–
	P8478	Clade 6	–	–	JN635083	–	EU079946	–
<i>Phytophthora ipomoeae</i>	P10225	Clade 1	–	–	JN635181	–	–	–
<i>Phytophthora iranica</i>	CBS374.72	Clade 1	–	–	–	HQ708314	HQ665219	–
<i>Phytophthora katsurae</i>	CBS587.85	Clade 5	–	–	–	HQ708315	HQ665278	–
	P10187	Clade 5	–	–	JN635173	–	–	–
<i>Phytophthora kelmania</i>	P10613	Clade 8	–	–	JN635103	–	–	–
<i>Phytophthora kernoviae</i>	P10958	Clade 10	–	–	–	HQ261349	EU080057	–
	P10958	Clade 10	–	–	JN635237	–	–	–
<i>Phytophthora lateralis</i>	CBS168.42	Clade 8	–	–	–	–	KJ128037	–
	Lev1213	Clade 8	–	–	–	HQ708320	–	–
<i>Phytophthora macrochlamyospora</i>	P1026	Clade 9	–	–	JN635190	–	–	–
<i>Phytophthora meadii</i>	CBS219.88	Clade 2	–	–	–	HQ708324	HQ665159	–
<i>Phytophthora medicaginis</i>	P7029	Clade 8	–	–	JN635096	–	–	–
<i>Phytophthora megakarya</i>	P1672	Clade 4	–	–	–	HQ261357	–	–
	P1672	Clade 4	–	–	JN635250	–	–	–
	P8516	Clade 4	–	–	–	–	EU079974	–
<i>Phytophthora megasperma</i>	CBS402.72	Clade 6	–	–	–	HQ708329	HQ665228	–

Table 1 (cont.)

Species	Strain Number	Clade	GenBank Accessions					
			SSU_ITS_28S	SSU_ITS	SSU	COI	LSU	ITS
<i>Phytophthora megasperma</i>	P10340	Clade 6	–	–	JN635176	–	–	–
<i>Phytophthora melonis</i>	CBS582.69	Clade 7	–	–	–	HQ708336	HQ665274	–
	P3609	Clade 7	–	–	JN635049	–	–	–
<i>Phytophthora mendei</i>	P10139	Clade 2	–	–	JN635038	–	–	–
<i>Phytophthora mirabilis</i>	CBS678.85	Clade 1	–	–	–	HQ708339	HQ665285	–
	P10231	Clade 1	–	–	JN635179	–	–	–
<i>Phytophthora multivesiculata</i>	CBS545.96	Clade 2	–	–	–	HQ708340	HQ665257	–
<i>Phytophthora multivora</i>	P1233	Clade 2	–	–	JN635155	–	–	–
<i>Phytophthora nemorosa</i>	P10288	Clade 3	–	–	JN635183	–	–	–
<i>Phytophthora nicotianae</i>	CBS303.29	Clade 1	–	–	–	HQ708352	–	–
	P10297	Clade 1	–	–	JN635184	–	–	–
	P7146	Clade 1	–	–	–	–	EU079560	–
<i>Phytophthora palmivora</i>	CBS298.29	Clade 4	–	–	–	HQ708357	HQ665195	–
	P0113	Clade 4	–	–	JN635188	–	–	–
	P0255	Clade 4	–	–	JN635186	HQ261382	EU080343	–
<i>Phytophthora parsiana</i>	P21281	Clade 9	–	–	JN635161	–	–	–
	P21282	Clade 9	–	–	JN635160	HQ261384	–	–
<i>Phytophthora phaseoli</i>	CBS556.88	Clade 1	–	–	–	HQ708359	HQ665267	–
	P10145	Clade 1	–	–	JN635167	–	–	–
<i>Phytophthora pinifolia</i>	P16100	Clade 6	–	–	–	HQ261390	–	–
	P16100	Clade 6	–	–	JN635272	–	–	–
<i>Phytophthora polonica</i>	P15004	Clade 9	–	–	–	HQ261394	EU080268	–
	P15005	Clade 9	–	–	JN635240	–	–	–
<i>Phytophthora porri</i>	CBS567.86	Clade 8	–	–	–	HQ708368	HQ665271	–
	P10728	Clade 8	–	–	JN635236	–	–	–
<i>Phytophthora primulae</i>	P10220	Clade 8	–	–	JN635180	–	–	–
	P10333	Clade 8	–	–	JN635187	HQ261397	EU080403	–
<i>Phytophthora pseudosyringae</i>	P10443	Clade 3	–	–	–	–	EU080026	–
	P16355	Clade 3	–	–	JN635257	HQ261399	–	–
<i>Phytophthora pseudotsugae</i>	CBS444.84	Clade 1	–	–	–	HQ708381	HQ665234	–
	P10218	Clade 1	–	–	JN635207	–	–	–
<i>Phytophthora quercetorum</i>	P15555	Clade 4	–	–	–	HQ261404	–	–
	PD01105	Clade 4	–	–	–	–	EU080905	–
<i>Phytophthora quercina</i>	P10334	Clade 4	–	–	JN635198	–	–	–
<i>Phytophthora quininea</i>	CBS407.48	Clade 9	–	–	–	HQ708386	HQ665230	–
	P3247	Clade 9	–	–	JN635110	–	–	–
<i>Phytophthora ramorum</i>	CBS101553	Clade 8	–	–	–	HQ708387	HQ665053	–
	P10301	Clade 8	–	–	JN635185	–	–	–
<i>Phytophthora richardiae</i>	P3876	Clade 8	–	–	JN635045	–	–	–
<i>Phytophthora rosacearum</i>	P8048	Clade 6	–	–	JN635062	–	–	–
	P8049	Clade 6	–	–	JN635057	–	–	–
<i>Phytophthora rubi</i>	CBS967.95	Clade 7	–	–	–	–	HQ665306	–
<i>Phytophthora sansomea</i>	P3163	Clade 8	–	–	JN635047	–	–	–
<i>Phytophthora sinensis</i>	CBS557.88	Clade 7	–	–	–	–	HQ665269	–
<i>Phytophthora siskiyouensis</i>	P15122	Clade 2	–	–	–	HQ261421	HQ665311	–
	P15123	Clade 2	–	–	–	–	HQ665312	–
	CBS382.61	Clade 7	–	–	–	–	HQ665224	–
<i>Phytophthora sojae</i>	CBS382.61	Clade 7	–	–	–	–	HQ665224	–
<i>Phytophthora sp aacrimae</i>	P15880	Clade 6	–	–	JN635255	–	–	–
<i>Phytophthora sp asparagi</i>	P10707	Clade 6	–	–	JN635226	–	–	–
<i>Phytophthora sp canalensis</i>	P10456	Clade 6	–	–	JN635174	–	–	–
<i>Phytophthora sp cuyabensis</i>	P8213	Clade 9	–	–	JN635084	–	–	–
<i>Phytophthora sp lagoriana</i>	P8220	Clade 9	–	–	JN635085	–	–	–
<i>Phytophthora sp napoensis</i>	P8225	Clade 9	–	–	JN635082	–	–	–
<i>Phytophthora sp niederhauserii</i>	P10617	Clade 7	–	–	JN635212	–	EU080247	–
<i>Phytophthora sp novaeguineae</i>	P3389	Clade 5	–	–	JN635067	–	–	–
<i>Phytophthora sp ohioensis</i>	P16050	Clade 4	–	–	JN635265	–	–	–
<i>Phytophthora sp personii</i>	P11555	Clade 6	–	–	JN635134	–	–	–
<i>Phytophthora sp sulawesiensis</i>	P6306	Clade 6	–	–	JN635095	–	–	–
<i>Phytophthora syringae</i>	CBS132.23	Clade 8	–	–	–	HQ708404	HQ665123	–
	P10330	Clade 8	–	–	JN635193	–	–	–
<i>Phytophthora tabaci</i>	CBS305.29	Clade 1	–	–	–	HQ708411	HQ665198	–
<i>Phytophthora tentaculata</i>	CBS552.96	Clade 1	–	–	–	HQ708413	HQ665264	–
	P10363	Clade 1	–	–	JN635192	–	–	–
<i>Phytophthora thermophilum</i>	P1896	Clade 9	–	–	JN635117	–	–	–
<i>Phytophthora trifolii</i>	P1462	Clade 8	–	–	JN635065	–	–	–
<i>Phytophthora tropicalis</i>	CBS434.91	Clade 2	–	–	–	HQ708417	HQ665233	–
<i>Phytophthora tropicalistype</i>	P10329	Clade 2	–	–	JN635099	–	–	–
<i>Phytophthora uliginosa</i>	P10328	Clade 7	–	–	JN635175	–	–	–
	P10413	Clade 7	–	–	JN635202	–	–	–
<i>Phytophthora boreale</i>	CBS551.88	Phytophthium	AY598662	–	–	HQ708419	–	–
<i>Phytophthora carbonicum</i>	CBS112544	Phytophthium	HQ643373	–	–	HQ708420	–	–
<i>Phytophthora chamaeaphyon</i>	CBS259.30	Phytophthium	AY598666	–	–	HQ708421	–	–
<i>Phytophthium citrinum</i>	CBS119171	Phytophthium	HQ643375	–	–	HQ708422	–	–
<i>Phytophthium delawarensis</i>	OH382/ CBS123040	Phytophthium	KF853241	–	–	KF853240	–	EU339312
<i>Phytophthium helicoides</i>	CBS286.31	Phytophthium	AY598665	–	–	HQ708430	–	–
<i>Phytophthium kandeliae</i>	CBS113.91	Phytophthium	–	–	–	HQ708206	HQ665079	HQ643133
	ATCC66501/P11614	Phytophthium	–	–	GU994166	–	–	–
<i>Phytophthium litorale</i>	CBS118360	Phytophthium	HQ643386	–	–	HQ708433	–	–
	CBS122662	Phytophthium	–	–	–	–	HQ665114	HQ643385
<i>Phytophthium mercuriale</i>	A89 (GENBANK)	Phytophthium	–	–	–	–	–	JN630486
	CBS122443	Phytophthium	KF853243	–	–	KF853239	KF853236	–
<i>Phytophthium mirpurensis</i>	CBS124523	Phytophthium	KJ831613	–	–	KJ831612	–	–
	CBS124524	Phytophthium	–	–	–	–	KJ831614	KJ831614

Table 1 (cont.)

Species	Strain Number	Clade	GenBank Accessions					
			SSU_ITS_28S	SSU_ITS	SSU	COI	LSU	ITS
<i>Phytophythium montanum</i>	CBS111349	Phytophythium	HQ643389	–	–	HQ708436	–	–
<i>Phytophythium oedochilum</i>	CBS292.37	Phytophythium	AY598664	–	–	HQ708439	–	–
<i>Phytophythium ostracodes</i>	CBS768.73	Phytophythium	AY598663	–	–	HQ708442	–	–
<i>Phytophythium sindhum</i>	CBS124518	Phytophythium	HQ643396	–	–	HQ708443	–	–
<i>Phytophythium vexans</i>	CBS119.80	Phytophythium	HQ643400	–	–	HQ708447	–	–
<i>Pythium abapressorium</i>	CBS110198	Clade F	HQ643408	–	–	HQ708455	–	–
<i>Pythium acanthicum</i>	CBS377.34	Clade D	AY598617	–	–	HQ708456	–	–
<i>Pythium acanthophoron</i>	CBS337.29	Clade J	AY598711	–	–	HQ708460	–	–
<i>Pythium acrogynum</i>	CBS549.88	Clade E	–	–	–	–	HQ665258	–
<i>Pythium adhaerens</i>	CBS520.74	Clade B	AY598619	–	–	HQ708462	–	–
<i>Pythium amasculinum</i>	CBS552.88	Clade D	AY598671	–	–	HQ708481	–	–
<i>Pythium anandrum</i>	CBS285.31	Clade H	AY598650	–	–	HQ708482	–	–
<i>Pythium angustatum</i>	CBS522.74	Clade B	AY598623	–	–	HQ708484	–	–
<i>Pythium aphanidermatum</i>	CBS118.80	Clade A	AY598622	–	–	HQ708485	–	–
<i>Pythium apiculatum</i>	CBS120945	Clade E	HQ643443	–	–	HQ708490	–	–
<i>Pythium apleroticum</i>	CBS772.81	Clade B	AY598631	–	–	HQ708491	–	–
<i>Pythium aquatile</i>	CBS215.80	Clade B	AY598632	–	–	–	HQ665153	–
<i>Pythium aristosporum</i>	CBS263.38	Clade B	AY598627	–	–	HQ708494	HQ665179	–
<i>Pythium arrhenomanes</i>	CBS324.62	Clade B	–	–	–	HQ708499	HQ665208	–
<i>Pythium atrantheridium</i>	DAOM230383	Clade F	–	–	–	HQ708524	HQ665308	–
	DAOM230386	Clade F	HQ643476	–	–	–	–	–
<i>Pythium buismaniae</i>	CBS288.31	Clade J	AY598659	–	–	–	HQ665188	–
<i>Pythium camurandrum</i>	CBS124096	Clade E	–	–	–	HQ708527	–	–
<i>Pythium canariense</i>	CBS112353	Clade G	–	–	–	HQ708528	HQ665069	–
<i>Pythium capillosum</i>	CBS222.94	Clade B	AY598635	–	–	HQ708529	HQ665164	–
<i>Pythium carolinianum</i>	CBS122659	Clade E	–	–	–	HQ708530	HQ665111	–
<i>Pythium catenulatum</i>	CBS842.68	Clade B	AY598675	–	–	HQ708540	HQ665302	–
<i>Pythium chondricola</i>	CBS203.85	Clade B	–	–	–	HQ708544	HQ665149	–
<i>Pythium coloratum</i>	CBS154.64	Clade B	AY598633	–	–	HQ708547	HQ665128	–
<i>Pythium conidiophorum</i>	CBS223.88	Clade B	AY598629	–	–	HQ708555	HQ665166	–
<i>Pythium contiguanum</i>	CBS221.94	Clade B	–	–	–	HQ708560	HQ665162	–
<i>Pythium cryptoirregularare</i>	CBS118731	Clade F	HQ643515	–	–	HQ708561	HQ665083	–
<i>Pythium cylindrosporium</i>	CBS218.94	Clade F	AY598643	–	–	HQ708562	HQ665157	–
<i>Pythium cystogenes</i>	CBS675.85	Clade J	HQ643518	–	–	HQ708564	HQ665284	–
<i>Pythium debaryanum</i>	CBS752.96	Clade F	AY598704	–	–	HQ708565	HQ665294	–
<i>Pythium deliense</i>	CBS314.33	Clade A	AY598674	–	–	HQ708568	HQ665204	–
<i>Pythium declinum</i>	CBS664.79	Clade B	–	–	–	HQ708570	HQ665282	–
<i>Pythium dimorphum</i>	CBS406.72	Clade H	AY598651	–	–	HQ708571	HQ665229	–
<i>Pythium dissimile</i>	CBS155.64	Clade B	AY598681	–	–	HQ708572	HQ665130	–
<i>Pythium dissotocum</i>	CBS166.68	Clade B	AY598634	–	–	HQ708574	HQ665139	–
<i>Pythium echinulatum</i>	CBS281.64	Clade E	AY598639	–	–	HQ708577	HQ665183	–
<i>Pythium emineosum</i>	BR479	Clade F	–	–	–	GQ244423	–	–
<i>Pythium erinaceus</i>	CBS505.80	Clade E	–	–	–	HQ708578	HQ665243	–
<i>Pythium flevoense</i>	CBS234.72	Clade B	AY598691	–	–	HQ708580	HQ665170	–
	CBS278.81	Clade B	–	–	–	–	HQ665182	–
	CBS220.94	Clade B	–	–	–	HQ708584	HQ665160	–
<i>Pythium folliculosum</i>	CBS120914	Clade I	HQ643543	–	–	–	HQ665091	–
<i>Pythium glomeratum</i>	CBS327.62	Clade B	AY598625	–	–	HQ708589	HQ665211	–
<i>Pythium graminicola</i>	CBS286.79	Clade C	AY598692	–	–	HQ708590	HQ665187	–
<i>Pythium grandisporangium</i>	CBS393.54	Clade H	AY598653	–	–	HQ708592	HQ665225	–
<i>Pythium helicandrum</i>	CBS450.67	Clade I	AY598654	–	–	HQ708597	HQ665235	–
<i>Pythium hydnosporum</i>	CBS253.60	Clade D	AY598672	–	–	HQ708608	HQ665175	–
<i>Pythium hypogynum</i>	CBS234.94	Clade E	AY598693	–	–	HQ708609	HQ665171	–
<i>Pythium inflatum</i>	CBS168.68	Clade B	AY598626	–	–	HQ708610	HQ665140	–
<i>Pythium insidiosum</i>	ATCC 58643	Clade C	AF289981	–	–	–	–	–
	CBS574.85	Clade C	–	–	–	HQ708614	HQ665273	–
<i>Pythium intermedium</i>	CBS266.38	Clade F	AY598647	–	–	HQ708616	HQ665180	–
<i>Pythium irregulare</i>	CBS250.28	Clade F	AY598702	–	–	HQ708640	HQ665172	–
<i>Pythium iwayamai</i>	CBS156.64	Clade G	AY598648	–	–	HQ708713	HQ665131	–
<i>Pythium kashmirensis</i>	ADC0819	Clade B	–	HQ643671	–	–	–	–
	CBS122908	Clade B	–	–	–	HQ708715	HQ665118	–
<i>Pythium kunmingense</i>	CBS550.88	Clade F	AY598647	–	–	–	HQ665259	–
<i>Pythium longisporangium</i>	CBS122646	Clade E	–	–	–	HQ708724	HQ665099	–
<i>Pythium lucens</i>	CBS113342	Clade F	HQ643681	–	–	HQ708725	HQ665077	–
<i>Pythium lutarium</i>	CBS222.88	Clade B	–	–	–	HQ643682	HQ665163	–
<i>Pythium lycopersici</i>	CBS122909	Clade D	–	–	–	HQ708727	HQ665119	–
<i>Pythium macrosporum</i>	CBS574.80	Clade F	AY598646	–	–	HQ708728	HQ665272	–
<i>Pythium marsipium</i>	CBS773.81	Clade E	–	–	–	HQ708734	HQ665297	–
<i>Pythium mastophorum</i>	CBS375.72	Clade J	AY598661	–	–	HQ708735	HQ665220	–
<i>Pythium megacarpum</i>	CBS112351	Phytophythium	–	–	–	–	–	HQ643388
<i>Pythium middletonii</i>	CBS528.74	Clade E	–	–	–	HQ708738	HQ665249	–
<i>Pythium minus</i>	CBS122657	Clade E	–	–	–	HQ708739	HQ665109	–
	CBS226.88	Clade E	AY598698	–	–	HQ643696	–	–
<i>Pythium monospermum</i>	CBS158.73	Clade A	HQ643697	–	–	HQ708741	HQ665137	–
<i>Pythium multisporum</i>	CBS470.50	Clade E	AY598641	–	–	HQ708744	HQ665239	–
<i>Pythium myriotyllum</i>	CBS254.70	Clade B	AY598678	–	–	HQ708745	HQ665176	–
<i>Pythium nagaii</i>	CBS779.96	Clade G	AY598705	–	–	HQ708749	HQ665299	–
<i>Pythium nodosum</i>	CBS102274	Clade J	–	–	–	HQ708753	HQ665055	–
<i>Pythium nunn</i>	CBS808.96	Clade J	AY598709	–	–	HQ708755	HQ665300	–
<i>Pythium okanoganense</i>	CBS315.81	Clade G	AY598649	–	–	–	HQ665205	–
<i>Pythium oligandrum</i>	CBS382.34	Clade D	AY598618	–	–	HQ708759	HQ665223	–
<i>Pythium oopapillum</i>	BR632	Clade B	–	–	–	FJ655178	–	–
<i>Pythium ornacarpum</i>	CBS112350	Clade E	HQ643721	–	–	HQ708762	HQ665066	–

Table 1 (cont.)

Species	Strain Number	Clade	GenBank Accessions					
			SSU_ITS_28S	SSU_ITS	SSU	COI	LSU	ITS
<i>Pythium ornamentatum</i>	CBS122665	Clade D	–	–	–	HQ708763	HQ665117	–
<i>Pythium orthogonon</i>	CBS376.72	Clade J	–	–	–	HQ708764	HQ665221	–
<i>Pythium pachycaule</i>	CBS227.88	Clade B	–	–	–	HQ708765	HQ665169	–
<i>Pythium paddicum</i>	CBS698.83	Clade G	AY598707	–	–	HQ708769	HQ665290	–
<i>Pythium paroecandrum</i>	CBS157.64	Clade F	AY598644	–	–	–	HQ665133	–
<i>Pythium parvum</i>	CBS225.88	Clade E	AY598697	–	–	HQ708779	HQ665167	–
<i>Pythium pectinolyticum</i>	CBS122643	Clade B	HQ643739	–	–	HQ708780	HQ665096	–
<i>Pythium perillum</i>	CBS169.68	Clade B	–	–	–	HQ708781	HQ665141	–
<i>Pythium periplocum</i>	CBS289.31	Clade D	AY598670	–	–	HQ708784	HQ665189	–
<i>Pythium perplexum</i>	CBS674.85	Clade J	AY598658	–	–	HQ708785	HQ665283	–
<i>Pythium pleroticum</i>	CBS776.81	Clade E	AY598642	–	–	HQ708789	HQ665298	–
<i>Pythium plurisporium</i>	CBS100530	Clade B	AY598684	–	–	HQ708790	HQ665052	–
<i>Pythium polymastum</i>	CBS811.70	Clade J	AY598660	–	–	HQ708793	HQ665301	–
<i>Pythium porphyrae</i>	CBS369.79	Clade A	AY598673	–	–	HQ708794	HQ665218	–
<i>Pythium prolatum</i>	CBS845.68	Clade H	AY598652	–	–	HQ708795	HQ665303	–
<i>Pythium pyrlobum</i>	CBS158.64	Clade B	AY598636	–	–	HQ708796	HQ665136	–
<i>Pythium radiosum</i>	CBS217.94	Clade E	–	–	–	–	HQ665156	–
<i>Pythium rhizooryzae</i>	CBS119169	Clade B	HQ643757	–	–	HQ708798	HQ665087	–
<i>Pythium rhizosaccharum</i>	CBS112356	Clade E	–	–	–	HQ708801	HQ665072	–
<i>Pythium rostratifingens</i>	CBS115464	Clade E	HQ643761	–	–	HQ708802	HQ665080	–
<i>Pythium rostratum</i>	CBS533.74	Clade E	AY598696	–	–	HQ708808	HQ665252	–
<i>Pythium salpingophorum</i>	CBS471.50	Clade B	AY598630	–	–	HQ708809	HQ665240	–
<i>Pythium scleroteichum</i>	CBS294.37	Clade B	AY598680	–	–	HQ708812	HQ665192	–
<i>Pythium segnitium</i>	CBS112354	Clade E	HQ643772	–	–	HQ708813	HQ665070	–
<i>Pythium senticosum</i>	CBS122490	Clade H	HQ643773	–	–	HQ708814	HQ665093	–
<i>Pythium sp balticum</i>	CBS122649	Clade F	–	–	–	HQ708525	–	–
<i>Pythium sp</i>	CBS113341	Clade F	KF853244	–	–	–	–	–
<i>Pythium sp CAL-2011a</i>	CBS122647	Clade D	–	–	–	HQ708815	–	–
<i>Pythium sp CAL-2011e</i>	CBS122648	Clade E	–	–	–	HQ708770	HQ665101	–
<i>Pythium sp CAL-2011f</i>	CBS101876	Clade J	HQ643778	–	–	HQ708819	–	–
<i>Pythium spiculum</i>	CBS122645	Clade F	KF853242	–	–	–	HQ665098	–
<i>Pythium spinosum</i>	CBS275.67	Clade F	AY598701	–	–	HQ708834	HQ665181	–
<i>Pythium splendens</i>	CBS462.48	Clade I	AY598655	–	–	HQ708836	HQ665237	–
<i>Pythium sterile</i>	B09	Phytophythium	–	–	–	–	–	EU240096
<i>Pythium sukuiense</i>	CBS110030	Clade B	–	–	–	HQ708877	HQ665059	–
<i>Pythium sylvaticum</i>	CBS453.67	Clade F	AY598645	–	–	HQ708886	HQ665236	–
<i>Pythium takayamanum</i>	CBS122491	Clade E	HQ643854	–	–	HQ708895	HQ665094	–
<i>Pythium terrestris</i>	CBS112352	Clade F	–	–	–	HQ708898	HQ665068	–
<i>Pythium torulosum</i>	CBS316.33	Clade B	AY598624	–	–	HQ708900	HQ665206	–
<i>Pythium tracheiphilum</i>	CBS323.65	Clade B	–	–	–	HQ708903	HQ665207	–
<i>Pythium ultimum</i> var. <i>sporangiferum</i>	CBS219.65	Clade I	AKYB02045405	–	–	HQ708920	HQ665158	–
<i>Pythium ultimum</i> var. <i>ultimum</i>	CBS398.51	Clade I	AY598657	–	–	HQ708906	HQ665227	–
<i>Pythium uncinulatum</i>	CBS518.77	Clade J	AY598712	–	–	HQ708985	HQ665244	–
<i>Pythium undulatum</i>	CBS157.69	Clade H	AY598708	–	–	HQ708987	HQ665134	–
<i>Pythium vanterpoolii</i>	CBS295.37	Clade B	AY598685	–	–	HQ708993	HQ665193	–
<i>Pythium viniferum</i>	CBS119168	Clade F	HQ643956	–	–	HQ708997	HQ665086	–
<i>Pythium violae</i>	CBS132.37	Clade G	AY598717	–	–	–	–	–
	CBS159.64	Clade G	AY598706	–	–	HQ708999	HQ665138	–
<i>Pythium volutum</i>	CBS699.83	Clade B	AY598686	–	–	HQ709012	HQ665291	–
<i>Pythium zingiberis</i>	CBS216.82	Clade B	–	–	–	HQ709014	HQ665155	–

(5'-AACTTAAAGGAATTGACGGAAG3') and NS8 (5'-TCCGCA-GGTTACCTACGGA3') (White et al. 1990) as well as Oom_Lo-5.8S47 (5'-ATTACGTATCGCAGTTCGAG3') (Man in 't Veld et al. 2002) for full bidirectional coverage. Sequencing reactions were prepared using the Big Dye Terminator (BDT) v. 2 protocols (Applied Biosystems, Foster City, CA). Sequencing of the PCR product was performed in an Applied Biosystems Prism Genetic Analyzer model 3130XL.

Phylogenetic analyses

Sequences were edited manually using the DNASTar Lasergene 9 Suite (Bioinformatics Pioneer DNASTar, Inc., WI) or Geneious v. 6.1.6 (Biomatters <http://www.geneious.com/>). Multiple alignments of each gene region were generated using MAFFT (Kato et al. 2005). The genera included in the phylogenetic analyses were *Albugo*, *Halophytophthora*, *Phytophthora*, *Phytophythium* and *Pythium*. Isolates of *Albugo candida* from the order *Albuginales* were included as an outgroup.

In order to include the maximum molecular data for clade K *Pythium* the invalid species *Pythium sterile* and *Pythium megarcarpum* as well as two strains of the novel species *Phytophythium mirpurensense* are considered in a cladogram generated based on ITS sequence data. *Pythium ultimum* from clade I

and *Pythium dimorphum* from clade H are outgroups in these analyses and representatives of *Phytophthora*, *P. infestans*, *P. ramorum* and *P. sojae* are included. The aligned data matrix from 23 strains contained 1 096 characters from the ITS1, ITS2 and the 5.8S gene.

The aligned data matrices were assessed to find the best-fit model of nucleotide substitution using jMODELTEST (Posada 2008). In each case this was identified as General Time Reversible (GTR+I+G). Redundant sequences were identified and those with 100 % identity to other included taxa were removed from the analyses. These duplicates are catalogued in Table 2. The aligned data matrices contained 1 374 bp of D1–D3 regions of LSU with 176 strains, 1 724 bp of SSU rRNA with 159 strains and 680 bp of COI with 174 strains. The sequence alignments were subjected to maximum likelihood analysis using the GTR+I+G substitution model and the Best option for tree topology search with PhyML v. 3.0 (Guindon & Gascuel 2003) to obtain ML trees which were rooted to *Albugo* (LSU, COI and SSU) or *Pythium* (ITS). Nonparametric ML bootstraps were calculated with 1 000 bootstrap replicates. Bayesian inferences (BI) were generated using MrBayes v. 3.2.1 (Ronquist & Huelsenbeck 2003) with Markov Chain Monte Carlo (MCMC) methodology to calculate posterior probabilities of the phylo-

Table 2 Species and isolates not included in the study for strains that were 100 % identical for certain genes and therefore not included in the phylogenetic analyses.

Sequence included in phylogeny				Identical sequences not included in phylogenies			
Species	Strain	Clade	GenBank	Species	Strain	Clade	GenBank
SSU							
<i>Phytophthora alticola</i>	P16053	Clade 4	JN635264	<i>Phytophthora frigida</i>	P16051	Clade 2	JN635162
<i>Phytophthora asparagi</i>	P10707	Clade 6	JN635226	<i>Phytophthora rosacearum</i>	P8048	Clade 6	JN635062
<i>Phytophthora cactorum</i>	P0714	Clade 1	JN635210	<i>Phytophthora cactorum</i>	P10365	Clade 1	JN635194
<i>Phytophthora captiosa</i>	P10719	Clade 9	JN635227	<i>Phytophthora captiosa</i>	P10720	Clade 9	JN635229
<i>Phytophthora cryptogea</i>	P16165	Clade 8	JN635259	<i>Phytophthora pseudosyringae</i>	P16355	Clade 3	JN635257
<i>Phytophthora erythroseptica</i>	P1693	Clade 8	JN635249	<i>Phytophthora gonapodyides</i>	P3700	Clade 6	JN635141
				<i>Phytophthora richardiae</i>	P3876	Clade 8	JN635045
				<i>Phytophthora sansomea</i>	P3163	Clade 8	JN635047
				<i>Phytophthora trifolii</i>	P1462	Clade 8	JN635065
<i>Phytophthora europaea</i>	P10324	Clade 7	JN635189	<i>Phytophthora uliginosa</i>	P10328	Clade 7	JN635175
<i>Phytophthora lagoriana</i>	P8220	Clade 9	JN635085	<i>Phytophthora uliginosa</i>	P10413	Clade 7	JN635202
				<i>Phytophthora lagoriana</i>	P8223	Clade 9	JN635086
<i>Phytophthora palmivora</i>	P0113	Clade 4	JN635188	<i>Phytophthora parsiana</i>	P21282	Clade 9	JN635160
<i>Phytophthora primulae</i>	P10220	Clade 8	JN635180	<i>Phytophthora palmivora</i>	P0255	Clade 4	JN635186
<i>Pythium flevoense</i>	CBS23472	Clade B	AY598691	<i>Phytophthora primulae</i>	P10333	Clade 8	JN635187
<i>Pythium minus</i>	CBS22688	Clade E	AY598698	<i>Pythium pectinolyticum</i>	CBS122643	Clade B	HQ643739
				<i>Pythium pleroticum</i>	CBS776.81	Clade E	AY598642
<i>Pythium porphyrae</i>	CBS36979	Clade A	AY598673	<i>Pythium parvum</i>	CBS225.88	Clade E	AY598697
<i>Pythium salinum</i>	CBS113341	Clade F	KF853244	<i>Pythium adhaerens</i>	CBS520.74	Clade B	AY598619
<i>Pythium spinosum</i>	CBS27567	Clade F	AY598701	<i>Pythium attrantheridium</i>	DAOM230386	Clade F	HQ643476
				<i>Pythium violae</i>	CBS132.37	Clade G	AY598717
				<i>Pythium lucens</i>	CBS113342	Clade F	HQ643681
<i>Pythium uncinulatum</i>	CBS51877	Clade J	AY598712	<i>Pythium kunmingense</i>	CBS55088	Clade F	AY598647
				<i>Pythium buismaniae</i>	CBS288.31	Clade J	AY598659
LSU							
<i>Phytophthora arecae</i>	CBS30562	Clade 4	HQ665200	<i>Phytophthora palmivora</i>	CBS29829	Clade 4	HQ665195
<i>Phytophthora boehmeriae</i>	CBS29129	Clade 10	HQ665190	<i>Phytophthora boehmeriae</i>	P6950	Clade 10	EU080166
<i>Phytophthora brassicae</i>	CBS17887	Clade 8	HQ665144	<i>Phytophthora brassicae</i>	CBS178.87	Clade 8	HQ665144
<i>Phytophthora erythroseptica</i>	CBS12923	Clade 8	HQ665121	<i>Phytophthora himalayensis</i>	CBS35759	Clade 8	HQ665215
<i>Phytophthora fragariae</i>	CBS20946	Clade 7	HQ665150	<i>Phytophthora rubi</i>	CBS96795	Clade 7	HQ665306
<i>Phytophthora gonapodyides</i>	CBS55467	Clade 6	HQ665265	<i>Phytophthora gonapodyides</i>	CBS36379	Clade 6	HQ665216
<i>Phytophthora inundata</i>	P8478	Clade 6	EU079946	<i>Phytophthora humicola</i>	CBS20081	Clade 6	HQ665148
				<i>Phytophthora inundata</i>	CBS21585	Clade 6	HQ665154
<i>Phytophthora melonis</i>	CBS58269	Clade 7	HQ665274	<i>Phytophthora sinensis</i>	CBS55788	Clade 7	HQ665269
<i>Phytophthora</i> sp. "niederhauserii"	P10617	Clade 7	EU080247	<i>Phytophthora sojae</i>	CBS38261	Clade 7	HQ665224
<i>Phytophthora siskiyouensis</i>	P15123	Clade 2	HQ665312	<i>Phytophthora siskiyouensis</i>	P15122	Clade 2	HQ665311
<i>Pythium amasculinum</i>	CBS55288	Clade D	HQ665263	<i>Pythium lycopersicum</i>	CBS122909	Clade D	HQ665119
				<i>Pythium oligandrum</i>	CBS38234	Clade D	HQ665223
<i>Pythium apleroticum</i>	CBS77281	Clade B	HQ665296	<i>Pythium aquatile</i>	CBS21580	Clade B	HQ665153
<i>Pythium buismaniae</i>	CBS28831	Clade J	HQ665188	<i>Pythium polymastum</i>	CBS81170	Clade J	HQ665301
<i>Pythium capillosum</i>	CBS22294	Clade B	HQ665164	<i>Pythium flevoense</i>	CBS27881	Clade B	HQ665182
				<i>Pythium flevoense</i>	CBS23472	Clade B	HQ665170
<i>Pythium catenulatum</i>	CBS84268	Clade B	HQ665302	<i>Pythium rhizo-oryzae</i>	CBS119169	Clade B	HQ665087
<i>Pythium viniferum</i>	CBS119168	Clade F	HQ665086	<i>Pythium debaryanum</i>	CBS75296	Clade F	HQ665294
COI							
<i>Phytophthora arecae</i>	CBS30562	Clade 4	HQ708218	<i>Phytophthora palmivora</i>	CBS29829	Clade 4	HQ643307
<i>Pythium amasculinum</i>	CBS55288	Clade D	HQ708481	<i>Pythium lycopersicum</i>	CBS122909	Clade D	HQ643683
				<i>Pythium ornamentatum</i>	CBS122665	Clade D	HQ708763
<i>Pythium conidiophorum</i>	CBS22388	Clade B	HQ708555	<i>Pythium salpingophorum</i>	CBS47150	Clade B	HQ643768
<i>Pythium debaryanum</i>	CBS75296	Clade F	HQ708565	<i>Pythium viniferum</i>	CBS119168	Clade F	HQ643956
<i>Pythium diclinum</i>	CBS66479	Clade B	HQ708570	<i>Pythium lutarium</i>	CBS22288	Clade B	HQ643682
<i>Pythium erinaceus</i>	CBS50580	Clade E	HQ708578	<i>Pythium ornacarpum</i>	CBS112350	Clade E	HQ643721
<i>Pythium folliculosum</i>	CBS22094	Clade B	HQ708584	<i>Pythium torulosum</i>	CBS31633	Clade B	HQ643859
<i>Pythium minus</i>	CBS122657	Clade E	HQ708739	<i>Pythium pleroticum</i>	CBS77681	Clade E	HQ643748
<i>Pythium myriotylum</i>	CBS25470	Clade B	HQ708745	<i>Pythium zingiberis</i>	CBS21682	Clade B	HQ643973

genetic trees. The program was run for 20 M generations for the LSU, 40 M generations for the COI, 50 M generations for the SSU and 10 M for the ITS datasets with the GTR+I+G model of evolution for each gene. The first 25 % of the iterations were discarded as burn-in and every 1 000th iteration was sampled from the remainder. The trees were considered to be fully converged when the average standard deviation of split frequencies reached a level less than 0.01. FigTree v. 1.3.1 (<http://tree.bio.ed.ac.uk/software/figtree/>) was used to view and edit ML and Bayesian phylogenetic trees. Consensus trees were generated using the 50 % majority rule tree criteria and rooted to *Albugo* (LSU, COI and SSU) or *Pythium* (ITS).

Statistical analyses of pairwise distances

The alignments of COI, LSU and SSU used for phylogeny were also used to generate pairwise distance as was done for DNA barcode analyses (Robideau et al. 2011, Schoch et al. 2012). Statistical analyses and plots were performed with R (R Development Core Team, 2011). All pairwise distances involving a *Phytophythium* species against *Pythium* or *Phytophthora* were extracted, i.e. all pairwise distances involving any two *Phytophythium* species were excluded. An arcsine transformation of the distances was done to improve the variance homogeneity. ANOVA using 'lm' was done with markers (COI/LSU/SSU), genera (*Phytophthora*/*Pythium*) or clades (clade 1–10 and A–J)

as variables. Plots were generated with 'ggplot' for R. The 0.05 confidence interval for 60 multiple comparisons was adjusted using the Bonferoni method. The average pairwise distance by marker was normalised to remove the bias from the difference in number of species between *Pythium* and *Phytophthora*.

Isolation and identification of *Phytophythium mirpurense*

Stagnant water was collected and immediately brought to the laboratory for the isolation of oomycetous fungi by the baiting technique of Harvey (1925). Grass blades, dicot leaves, hemp seeds, sesame seeds, lemon leaf and young cucumber stems were used as baits. Plates were incubated at room temperature, between 22–25 °C. Hyphae were observed on the baits after 5–8 days of incubation. The baits were rinsed in sterilised water

to remove excess contaminants and transferred to fresh plates half-filled with sterile water. New fresh baits were then added and monitored daily for colonisation by oomycetes. After 2 d of incubation, the baits colonised by oomycetous fungi were transferred onto corn-meal agar (CMA) medium for purification by hyphal tip transfer. To obtain a pure culture a small disc of the CMA culture was placed into the centre of water agar plates. After 15–24 h growing apical hyphae were cut with the aid of a microscope in the laminar flow hood and transferred onto the surface of a fresh plate containing culture media.

For the assessment of cardinal temperatures, the isolates from this study were sub-cultured in two replicates on CMA in 90 mm Petri plates, and incubated at 10, 15, 20, 25, 30, 35 and 40 °C for 5 d. Radial growth was measured daily along

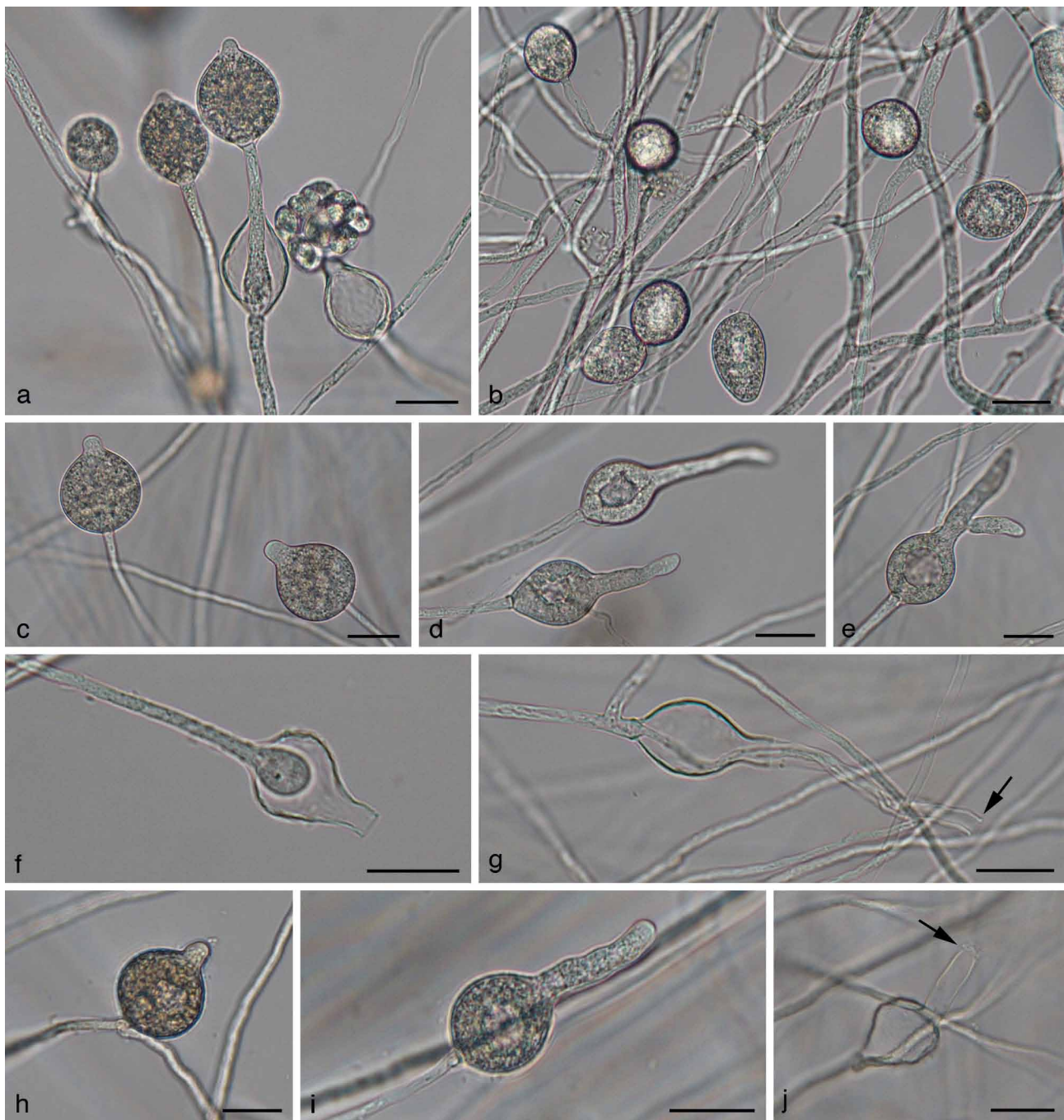


Fig. 1 Sporangia of *Phytophythium* species. a. *P. sindhum*, four stages of sporangium development showing a young, globose sporangium, a mature, papillate sporangium, internal proliferation and pythium-like zoospore development; b. *P. vexans*, subglobose, non-papillate sporangia; c–g. *P. citrinum*: c. normal sporangia; d. outgrowing papillae; e. outgrowing and branching papilla; f. empty sporangium with internal proliferation and short discharge tube; g. empty sporangium with internal proliferation and long discharge tube (arrow indicating tip); h–j. *P. heliandrum*: h. sessile, globose, papillate sporangium; i. outgrowing papilla; j. empty sporangium with intermediate sized discharge tube (arrow indicating tip). — Scale bars = 20 µm.

two lines intersecting the centre of the inoculum. Isolates were also grown on potato dextrose agar (PDA), potato carrot agar (PCA), CMA and corn meal dextrose agar (CMDA) in 90 mm Petri plates (recipes according to Crous et al. 2009), and colony characteristics were assessed after incubation for 5 d at 25 °C. Water cultures for zoospore and sporangial production were prepared by adding an inoculum disc and a grass blade to sterile water in a Petri plate and incubating at 25 °C. Biometric values i.e. aplerotic index, ooplast index and wall index were determined for 20 oogonia with the method described by Shahzad et al. (1992).

RESULTS AND DISCUSSION

Morphological comparison of *Phytophythium* with *Phytophthora* and *Pythium*

Most species in the genus *Phytophythium* produce papillate, internally proliferating sporangia (Fig. 1). The shape of the sporangia is more or less similar to the shape of papillate *Phytophthora* sporangia: (sub-)globose to ovoid and papillate (Fig. 1). However, in *Phytophthora* the papillate sporangium type never shows internal proliferation. The combination of internal proliferation and papillation (Fig. 1) is unique to sporangia of *Phytophythium* and some *Pythium* species (see below). Also, the papillae in *Phytophythium* are different from the papillae in *Phytophthora* sporangia. In *Phytophythium* the sporangia are initially non-papillate, and the papillae develop at maturity and do not consist of a hyaline 'apical thickening' as in *Phytophthora* (Blackwell 1949). They may grow out to form a shorter or larger discharge tube (Fig. 1d, f, g, i, j), which does not occur in *Phytophthora*. In some species the papilla is not the place where the plasma flows out, rather one or more discharge tubes are formed more basally of the sporangium. In some species the papilla grows out and develops branches (Fig. 1e). Another difference with *Phytophthora* is the zoospore discharge which is pythium-like in *Phytophythium*: the plasma flows out of the sporangium through a discharge tube to form a plasma-filled

vesicle at the tip. Zoospores are developed outside the sporangium, within the vesicle membrane and are released after rupture of the membrane (Fig. 1a). According to Marano et al. (2014), *Phytophythium kandeliae* has zoospore release mostly like *Pythium* and occasionally in between *Pythium* and *Phytophthora*: zoospores developed (partly) inside a sporangium and partly in a vesicle.

Another unique characteristic of *Phytophythium* is the shape of the antheridium (Fig. 2). In most species the antheridia are elongate, cylindrical, often with constrictions. The fertilisation tube is mostly not apical but in 'navel position' (Fig. 2a–d, arrows). Occasionally club-shaped antheridia with apical attachment occur. In *P. vexans*, the antheridia are often very broadly attached to the oogonium and lobed (Fig. 2e, f).

Papillate sporangia with internal proliferation also occur in a small number of *Pythium* species: three members of clade E (*P. marsipium*, *P. middletonii*, *P. multisporum*), one member of clade G (*P. nagaii*) and clade C (*P. grandisporangium*) and all members of clade H (*P. anandrum*, *P. dimorphum*, *P. helicandrum*, *P. prolatum*, *P. undulatum*). However, none of these species except three has elongate, cylindrical or lobate antheridia. Only *P. helicandrum* has elongate antheridia, however, this species has ornamented oogonia and much bigger sporangia than any of the species in *Phytophythium*. *Pythium marsipium* has bell-shaped antheridia as they occur in *Phytophythium vexans*, however, its sporangia are utriform instead of ovoid. *Pythium grandisporangium* has lobate antheridia but this is a marine species with extremely large sporangia with a tapering neck rather than a distinct papilla.

Phylogenetic position of *Phytophythium*

Maximum likelihood analyses of nuclear (LSU and SSU) and mitochondrial DNA (COI) with Bayesian probability values mapped onto the trees are shown (Fig. 3A–C). These cladograms place all the strains belonging to the genus *Phytophythium* as a monophyletic group with bootstrap support (85–100 %) and high probabilities (0.99–1.00). Phylogenetic trees of the LSU

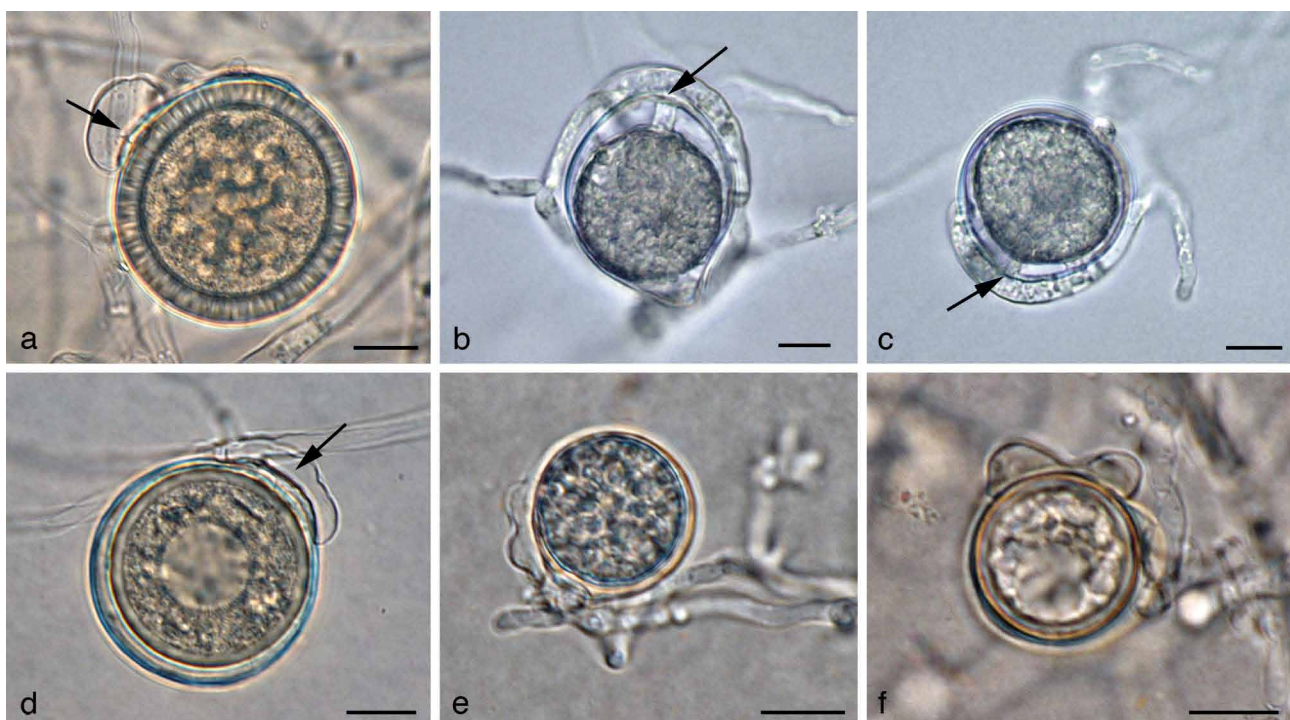


Fig. 2 Oogonia and antheridia of *Phytophythium* species. a. *P. sindhum*, slightly elongated antheridium; b–c. *P. oedochilum*, long cylindrical antheridia; d. *P. mirpurens*, elongate antheridium with slight constriction; e–f. *P. vexans*: e. elongate antheridium with distinct constrictions; f. antheridium with two lobes. Arrows indicate the fertilisation tube in navel position (a–d). — Scale bars = 10 µm.

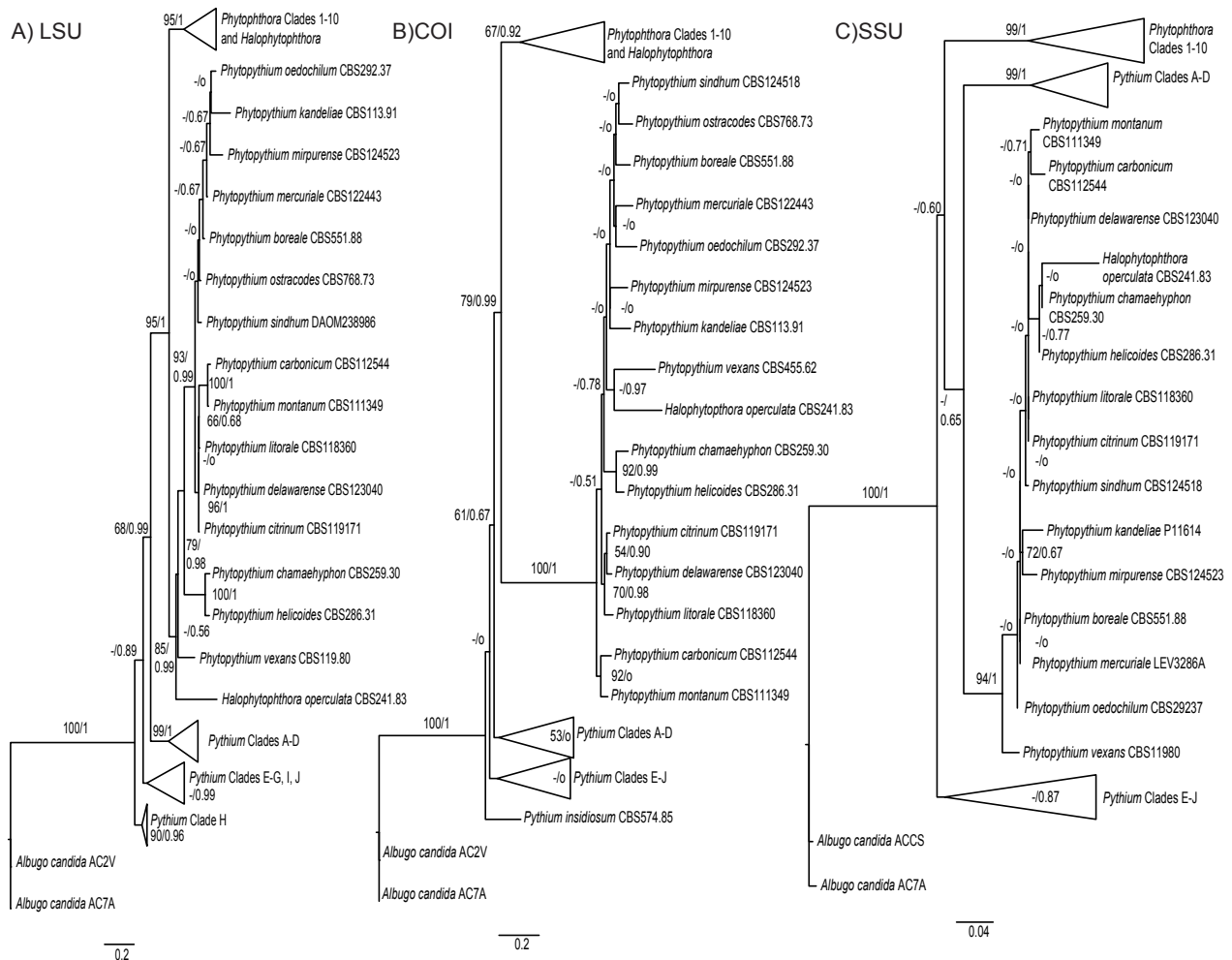


Fig. 3 Maximum likelihood phylogenetic trees of: a. LSU ribosomal RNA region; b. mitochondrial COI; c. SSU ribosomal RNA region. Maximum likelihood bootstrap support values larger than 50 % are indicated numerically, those under 50 % are marked (–). Posterior probability values larger than 0.50 are labelled numerically, those under 0.50 are marked (–) on each branch, those clades which were not present in the Bayesian trees are marked as (o), the scale bars represent the average number of substitutions per site.

and COI regions support this group as intermediary between *Phytophthora* and *Pythium*. There is phylogenetic support with two of the genes to group *Phytophythium* with *Phytophthora* (95 % / 1.00 for LSU and 79 % / 0.99 for COI). The SSU tree has *Pythium* clades A–D as grouping closer to *Phytophthora* and *Halophytophthora*, with very low bootstrap support and probabilities (< 50 % / 0.65). This suggests that given the SSU dataset, the major clades are unresolved in relation to the outgroup.

Our results from phylogenetic analysis of nuclear (LSU and SSU) and mitochondrial (COI) genes with all available species of *Pythium* and *Phytophthora* support that *Phytophythium* is a distinct genus. Its placement as intermediate between *Pythium* and *Phytophthora* is supported by two of these datasets. In the three gene trees, this new genus clade was strongly supported by both ML bootstrap replicates and Bayesian probability values, which unambiguously confirmed the status of *Phytophythium* as a novel monophyletic genus. The maximum likelihood and Bayesian analyses did not clearly delineate the relationships between the different groups in the part of the oomycete evolutionary tree we focused on. Inclusion of some of the more basal groups such as the *Salisapiliaceae* (Hulvey et al. 2010) and additional markers in future analyses would likely lead to greater resolution of these relationships.

The ITS tree (Fig. 4) shows that the two strains of species *P. mirpurensis* are both well embedded within *Phytophythium* with strong support (91 % / 0.96) and demonstrated the close

relationships between *P. litorale* and *Pythium sterile* (100 / 1) as well as *Phytophythium boreale* and *Pythium megacarpum* (99 / 1).

Statistical analyses of pairwise distances

Markers, genera and clades as well as interactions between them all had a significant effect on pairwise distances of *Phytophythium* against *Pythium* and *Phytophthora* species ($p < 10^{-15}$). The average pairwise distance of all *Phytophthora* species against all *Phytophythium* species using COI was 13.7 % whereas it was 14.5 % for all *Pythium* species against all *Phytophythium*, showing that *Phytophythium* is significantly closer to *Phytophthora* than *Pythium* ($p < 10^{-16}$). For LSU, these differences were 10.4 % and 10.9 %, respectively, and were also significant ($p < 10^{-16}$). For SSU, the trend was reversed, still significant, with the average pairwise distance between *Pythium* and *Phytophythium* being 2.5 % whereas the average between *Phytophthora* and *Phytophythium* was 2.7 %. The clade effect was significant, including a significant interaction with markers; therefore, the results are presented by clades and markers in Fig. 5. Each clade is compared against *Phytophythium* to show clades that have a significant difference from the average pairwise distance. The significant trend of *Phytophythium* being closer to *Phytophthora* clades than *Pythium* clades can be seen with COI and LSU whereas it is more difficult to visualise the reverse trend in SSU. With all markers, *Pythium* clades H and I were significantly closer to *Phytophythium* than were the other *Pythium* clades but for SSU there were three additional clades (B, F and G) that were significantly closer to *Phytophythium* than were the other clades.

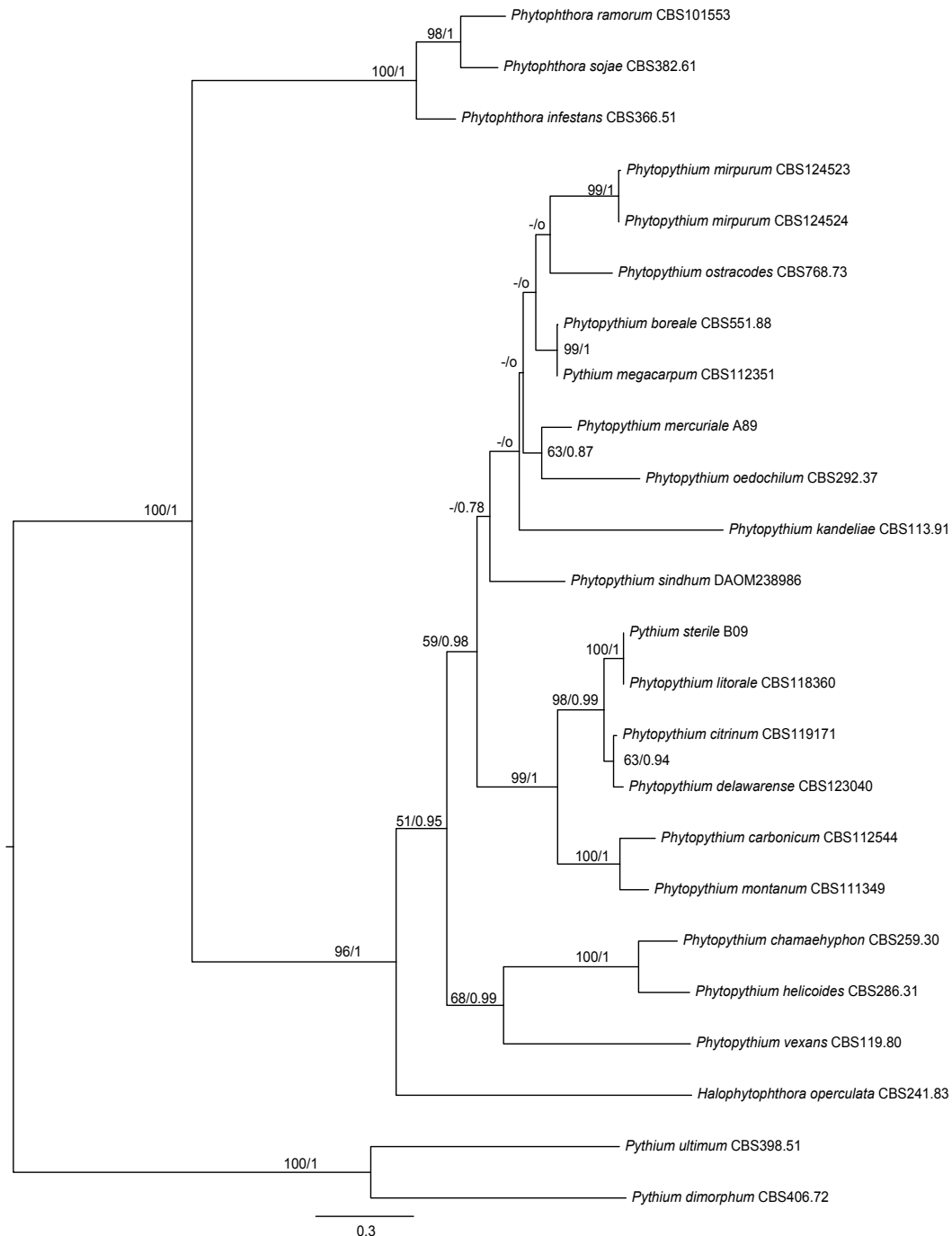


Fig. 4 Maximum likelihood tree of internal transcribed spacer (ITS) region of *Phytophythium* spp., *Pythium* spp. and *Phytophthora* spp. Maximum likelihood bootstrap support values larger than 50 % are indicated numerically, those under 50 % are marked with (-). Posterior probability values larger than 0.50 are labelled numerically, on each branch those clades which were not present in the Bayesian trees are marked as (o), the scale bars represent the average number of substitutions per site.

Strains used in circumscription of the genus

There are two invalid species that were investigated for the sake of examining the complete range of *Pythium* species from clade K, namely *Pythium megacarpum* and *P. sterile*. *Pythium megacarpum* is an invalid species because no type was indicated at the time of publication. Lévesque & de Cock (2004) placed it as potentially synonymous with *Phytophythium boreale* and in the barcode analyses of Robideau et al. (2011) these two species were only distinguishable through COI sequence data analysis, not by ITS. *Pythium sterile* is an invalid taxon based on the nomination of two herbarium specimens as the type of this species; this contravenes Art. 40.3 of the Melbourne convention (McNeill et al. 2012). *Pythium sterile* possesses identical ITS sequences to *Phytophythium litorale*. Other sequences from this organism could not be compared since no strain of *Pythium sterile* is

available. Both species do not produce sexual stages. A more extensive study of these pairs of species, namely, *Phytophythium boreale* / *Pythium megacarpum* and *Phytophythium litorale* / *Pythium sterile* including more isolates and more DNA regions should reveal whether *P. sterile* and *P. megacarpum* should be validated as legitimate species.

There were some clade K species which were not included in the phylogenetic analyses presented here. In the studies by Lévesque & de Cock (2004) and Robideau et al. (2011) the species *Pythium indigoferae* appeared in clade K, which is now the genus *Phytophythium*. In stark contrast to the other species in clade K, *Pythium indigoferae* produces filamentous sporangia according to its original description (Butler 1907). The strain of *Pythium indigoferae* in the study of Lévesque & de Cock (2004) was the strain CBS 261.30 which was used by

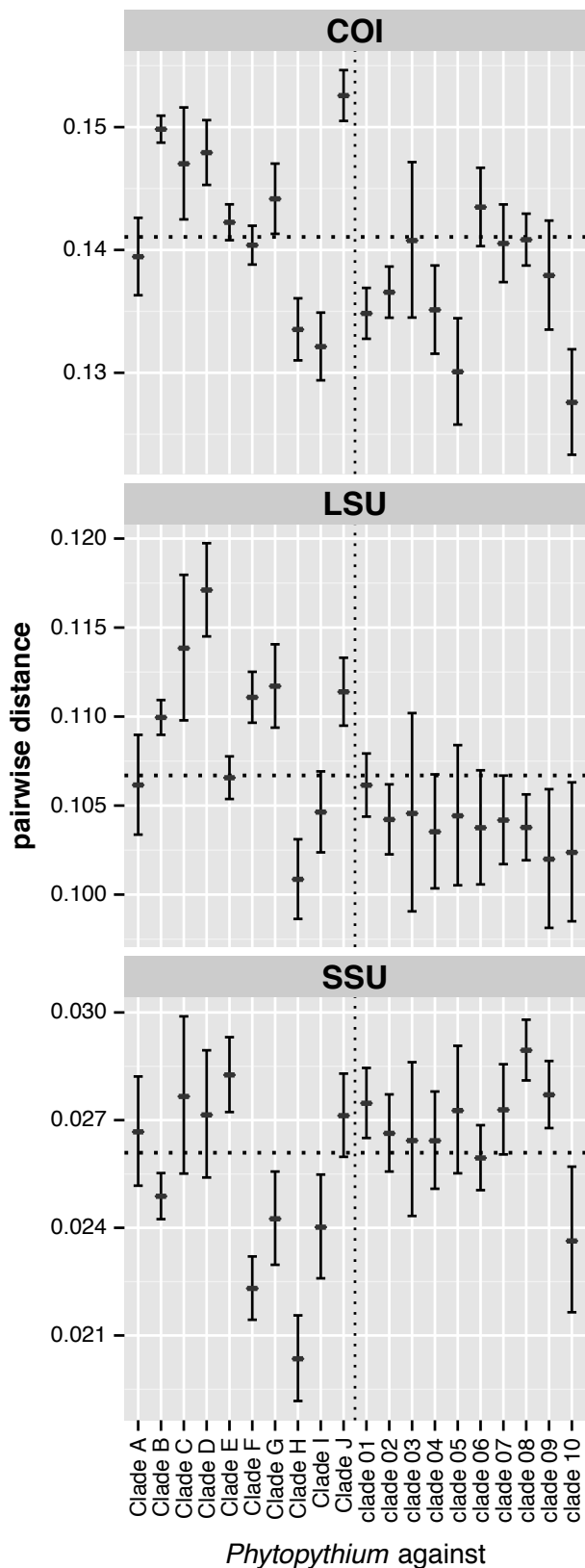


Fig. 5 Analysis of all pairwise distances containing only one representative of each *Phytophythium* sp. The dotted lines represent the average of all these pairwise distances for each marker, adjusted to remove the bias for the difference in species number between *Pythium* and *Phytophthora*. The bars represent 95 % confidence intervals corrected by the Bonferroni method for 60 comparisons. The analysis was done with arcsine transformation, therefore, the averages as well as the upper and lower boundaries of the intervals were transformed back to actual pairwise distances for the plot. Intervals that are not touching the average dotted line are significantly below or above the average, i.e. closer to or more distant to *Phytophythium*, respectively.

van der Plaats-Niterink (1981) in her publication 'Monograph of the genus *Pythium*', as the ex-type strain was no longer available. However, CBS 261.30 is also no longer viable. Under observation by van der Plaats-Niterink and more recently while it was still culturable, this strain did not sporulate. The identity of this strain can therefore not be confirmed. Other strains with DNA sequences very close to CBS 261.30 have been identified (unpubl. data) which produced, however, subglobose, proliferating, papillate sporangia. These findings agree with Spies et al. (2011) who suggested that this strain be re-identified as *Pythium vexans*. CBS 261.30 and related strains are clearly part of a *Phytophythium vexans* complex that needs to be resolved through further phylogenetic study. This *P. vexans* complex also contains the invalid taxon *Pythium cucurbitacearum*, which was not included in our analyses. This taxon is invalid as it is missing a Latin diagnosis and based on Art. 36 of the Melbourne convention (McNeill et al. 2012). The representative strain of *P. cucurbitacearum* CBS 748.96 is no longer viable. The ITS sequence of this strain was reported by Spies et al. (2011), to be related yet distinct from a novel strain isolated from *Acacia* which was very different among the isolates in the monophyletic *Phytophythium vexans* complex studied. Most likely strain CBS 748.96 represents a distinct species from the *P. vexans* complex, which as of yet is not validly described. Once this complex is resolved it is likely that it will represent a number of new species for the genus *Phytophythium*.

Two other *Pythium* species not included in the phylogenetic analyses are *P. palingenes* and *P. polytylum*. Because no living strains of these species are available, they could not be included in the DNA studies. Morphological data for *P. palingenes* and *P. polytylum* show the typical characters of *Phytophythium*: ovoid, papillate, internally proliferating sporangia and cylindrical antheridia. Therefore we consider *P. palingenes* and *P. polytylum* as members of *Phytophythium*.

A new species of *Phytophythium* was isolated from water samples collected in District MirpurKhas of Sindh province, Pakistan. It is described and illustrated here as *P. mirpurensis* (see section New Species). Genetically, *Phytophythium mirpurensis* is shown to nestle within the genus *Phytophythium*, in all of the phylogenetic trees presented. The most obvious morphological characters of this new species are the proliferating, subglobose sporangia, terminal and intercalary oogonia, antheridia with lengthwise application to oogonia over their entire length, aplerotic to nearly plerotic oospores, and high optimum temperature for growth. These characters are shared with many other members of *Phytophythium*. The main differentiation of this species is shown through the molecular analyses of DNA sequences and the phylogenetic trees (Fig. 3, 4).

Halophytophthora s.l. is a heterogenous, polyphyletic genus (Hulvey et al. 2010) with species of marine origin. Two species of this genus clustered within the clade of *Phytophythium*: *H. operculata* (originally described as *Phytophthora operculata*) and *H. kandeliae*. Further, only species of *Halophytophthora* s.str. (Hulvey et al. 2010) show some morphological similarity to *Phytophythium*. However, their sporangia are in average two or more times the size of sporangia in the *Phytophythium* species (length av. 64–117 μm , resp. 20–40 μm). They develop zoospores inside the sporangium and not in a vesicle like *Pythium*, though the formation of a vesicle may be part of the release process. Moreover, no internal proliferation was observed in these species. *Halophytophthora kandeliae* was previously transferred to *Phytophythium* (Marano et al. 2014, Thines 2014). The strains of *Halophytophthora kandeliae* used in barcode analyses of ITS and COI regions were CBS 111.91 and CBS 113.91 and they were both found to be associated with the *Phytophythium* clade (Robideau et al. 2011). However, neither of these strains is the type strain of this species. Marano et al. (2014) have published

the ITS sequence of the type strain of *H. kandeliae* from ATCC and this sequence was identical to that of CBS 111.91 and 113.91. We have then included data from strain CBS 113.91 in our analyses here and are certain that it well represents the systematic placement of *Phytopythium kandeliae*. There are some difficulties with *Halophytophthora operculata*'s lack of fit in this clade by morphological measures and we have decided not to rename it at this time. This marine species has zoospore development fully within the sporangium; no vesicle occurs. Zoospore discharge is unique, via an operculum at the apex of the sporangium and no internal proliferation was observed. The size of the sporangia is significantly much larger than those of the *Phytopythium* species (up to 175 µm). The strain CBS 241.83, which is the ex-type strain of *H. operculata*, did not sporulate during our investigations, so the identity of the strain could not be confirmed. However the current molecular data available about this strain, the sequence data presented here and the organisation of the 5S gene family as reported by Bedard et al. (2006), does indicate that it belongs in a monophyletic circumscription of *Phytopythium*. More investigation of this species is clearly required in order to confirm its identity.

New combinations were deposited in MycoBank (see below in section Taxonomic and Nomenclatural Changes; Crous et al. 2004).

CONCLUSIONS

The genus *Phytopythium* was first proposed to the community in 2008 (see www.phytophthoradb.org/pdf/O8LevesquePM.pdf) and it was formally published in June 2010 (Bala et al. 2010b), with *Phytopythium sindhum* as the type species. In 2010, Uzuhashi et al. (2010) proposed another name *Ovatisporangium* for clade K using a partial sampling of *Pythium* and *Phytophthora* species and published their findings in September of 2010. Comparison of their circumscription of the genus *Ovatisporangium* to our molecular analyses clearly shows that the type of *Phytopythium*, *P. sindhum* is a member of the group described as *Ovatisporangium* (Fig. 1, 2). *Ovatisporangium* is thus recognised as a synonym of *Phytopythium*.

We demonstrated with three different phylogenetic markers that all species belonging to *Pythium* clade K represent a monophyletic genus that includes the type species of the previously described genus *Phytopythium*. The taxonomic circumscription of other *Pythium* clades remains unresolved. The species with filamentous and globose sporangia are well separated as reported before in many studies, however, both LSU and COI suggest that clades A–J could be divided into subgroups but provide no support for any particular arrangement. The inclusion of species from other genera closely related to *Pythium* such as *Pythiogeton*, *Lagenidium* or *Myzocytiopsis* can change these conclusions but clade support remains very low (Schroeder et al. 2013, Hyde et al. 2014). Therefore, we recommend avoiding any further changes in the generic status of *Pythium* Pringsheim species belonging to clade A–J until better phylogenetic markers are found and multigene phylogenies are available with the closely related genera.

TAXONOMIC AND NOMENCLATURAL CHANGES

Phytopythium Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *Persoonia* 24: 137. 2010

Type species. Phytopythium sindhum, Lodhi, Shahzad & Lévesque, *Persoonia* 24: 137. 2010.

Etymology. Named after combined features of the genera *Phytophthora* and *Pythium*.

Common morphological characteristics of the species of *Phytopythium* are globose to ovoid shape of sporangia, often with a more or less distinct papilla or non-papillate and often proliferating internally like those in *Phytophthora* with non-papillate sporangia. Zoospore discharge is like *Pythium*. Most species have large, smooth oogonia, thick-walled oospores, and 1–2 elongate or lobate antheridia, laterally applied to the oogonium. Cultures are mostly homothallic, occasionally sterile.

Notes — *Phytopythium* (Bala et al. 2010b) is emended to include species of *Pythium* in clade K from Lévesque & de Cock (2004) and described after that. It is morphologically and phylogenetically between *Pythium* and *Phytophthora*.

NEW COMBINATIONS

Phytopythium boreale (R.L. Duan) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563326

Basionym. Pythium boreale R.L. Duan, *Acta Mycol. Sin.* 4: 1. 1985 (as '*borealis*') (MB105742).

≡ *Ovatisporangium boreale* (R.L. Duan) Uzuhashi, Tojo & Kakish., *Mycoscience* 51: 360. 2010 (MB517560).

Representative strain — CHINA, soil under *Brassica caulorapa*, CBS 551.88 (ex-type strain not available).

Phytopythium carbonicum (B. Paul) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563328

Basionym. Pythium carbonicum B. Paul, *FEMS Microbiol. Lett.* 219: 270. 2003 (MB489329).

≡ *Ovatisporangium carbonicum* (B. Paul) Uzuhashi, Tojo & Kakish., *Mycoscience* 51: 360. 2010 (MB517561).

Representative strain — FRANCE, soil on top of spoil heap, CBS 112544 (ex-type strain).

Phytopythium chamaehyphon (Sideris) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563329

Basionym. Pythium chamaehyphon Sideris, C.P., *Mycologia* 24: 33. 1932 (as '*chamaihyphon*') (MB260414).

≡ *Ovatisporangium chamaehyphon* (Sideris) Uzuhashi, Tojo & Kakish., *Mycoscience* 51: 360. 2010 (MB517562).

Representative strain — USA, Hawaii, *Carica papaya*, CBS 259.30 (ex-type strain).

Phytopythium citrinum (B. Paul) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563330

Basionym. Pythium citrinum B. Paul, *FEMS Microbiol. Lett.* 234: 273. 2004 (MB368597).

≡ *Ovatisporangium citrinum* (B. Paul) Uzuhashi, Tojo & Kakish., *Mycoscience* 51: 360. 2010 (MB517563).

Representative strain — FRANCE, Marsaunay la cote, vineyard soil, CBS 119171 (ex-type strain).

Phytopythium delawareense (Broders, P.E. Lipps, M.L. Ellis & Dorrance) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB807542

Basionym. Pythium delawareense Broders, P.E. Lipps, M.L. Ellis & Dorrance, *Mycologia* 104: 789. 2012 (MB563353).

Representative strain — USA, Ohio, Delaware county, *Glycine max*, CBS 123040 (ex-type strain).

Phytophythium helicoides (Drechsler) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563332

Basionym. *Pythium helicoides* Drechsler, J. Wash. Acad. Sci. 20: 413. 1930 (MB266912).

= *Ovatisporangium helicoides* (Drechsler) Uzuhashi, Tojo & Kakish., Mycoscience 51: 360. 2010 (MB517559).

= *Phytophthora fagopyri* S. Takim. ex S. Ito & Tokun., Trans. Sapporo Nat. Hist. Soc. 14: 15. 1935 (MB472184).

Representative strain — USA, *Phaseolus vulgaris*, CBS 286.31 (authentic strain).

Phytophythium litorale (Nechw.) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563335

Basionym. *Pythium litorale* Nechw., FEMS Microbiol. Lett. 255: 99. 2006 (MB521454).

= *Ovatisporangium litorale* (Nechw.) Uzuhashi, Tojo & Kakish., Mycoscience 51: 360. 2010 (MB517566).

Representative strain — GERMANY, Lake Konstanz, rhizosphere soil (*Phragmites australis*), CBS 118360 (ex-type strain).

Phytophythium mercuriale (Belbahri, B. Paul & Lefort) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563337

Basionym. *Pythium mercuriale* Belbahri, B. Paul & Lefort, FEMS Microbiol. Lett. 284: 20. 2008 (MB511433).

= *Ovatisporangium mercuriale* (Belbahri, B. Paul & Lefort) Uzuhashi, Tojo & Kakish., Mycoscience 51: 360. 2010 (MB517568).

Representative strain — SOUTH AFRICA, Limpopo Province, ex rhizosphere *Macadamia integrifoliae*, CBS 122443 (ex-type strain).

Phytophythium montanum (Nechw.) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563338

Basionym. *Pythium montanum* Nechw., Mycol. Progr. 2: 79. 2003 (MB373239).

= *Ovatisporangium montanum* (Nechw.) Uzuhashi, Tojo & Kakish., Mycoscience 51: 360. 2010 (MB517569).

Representative strain — GERMANY, Bavarian Alps, wet soil under *Picea abies*, CBS 111349 (ex-type strain).

Phytophythium oedochilum (Drechsler) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563339

Basionym. *Pythium oedochilum* Drechsler, J. Wash. Acad. Sci. 20: 414. 1931 (MB272763).

= *Ovatisporangium oedochilum* (Drechsler) Uzuhashi, Tojo & Kakish., Mycoscience 51: 360. 2010 (as 'oedichilum') (MB517570).

Representative strain — USA, CBS 292.37 (authentic strain).

Phytophythium ostracodes (Drechsler) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563340

Basionym. *Pythium ostracodes* Drechsler, Phytopathology 33: 286. 1943 (MB290364).

= *Ovatisporangium ostracodes* (Drechsler) Uzuhashi, Tojo & Kakish., Mycoscience 51: 360. 2010 (MB517571).

Representative strain — SPAIN, clay soil, CBS 768.73 (strain used by van der Plaats-Niterink (1981), ex-type strain not available).

Phytophythium palingenes (Drechsler) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB807543

Basionym. *Pythium palingenes* Drechsler, J. Wash. Acad. Sci. 20: 416. 1930 (MB273284).

Representative strain — None available.

Phytophythium polytylum (Drechsler) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB807544

Basionym. *Pythium polytylum* Drechsler, J. Wash. Acad. Sci. 20: 415. 1930 (MB275012).

Representative strain — None available.

Phytophythium vexans (de Bary) Abad, De Cock, Bala, Robideau, Lodhi & Lévesque, *comb. nov.* — MycoBank MB563322

Basionym. *Pythium vexans* de Bary, J. R. Agric. Soc. 12 (Ser. 2,1): 255. 1876 (MB174427).

= *Ovatisporangium vexans* (de Bary) Uzuhashi, Tojo & Kakish., Mycoscience 51: 360. 2010 (MB517573).

= *Pythium complectens* M. Braun, J. Agric. Res. 29: 415. 1924 (MB261556).

= *Pythium allantocladon* Sideris, Mycologia 24: 27. 1932 (MB256394).

= *Pythium ascophallon* Sideris, Mycologia 24: 29. 1932 (MB257476).

= *Pythium polycladon* Sideris, Mycologia 24: 32. 1932 (MB274913).

= *Pythium euthyhyphon* Sideris, Mycologia 24: 34. 1932 (MB536649).

= *Pythium piperinum* Dastur, Proc. Indian Acad. Sci., B 1, 11: 803. 1935 (MB274563).

Representative strain — IRAN, soil, CBS 119.80 (strain used by van der Plaats-Niterink (1981) ex-type strain not available).

NEW SPECIES

Phytophythium mirpureense Lodhi, De Cock, Lévesque & Shahzad, *sp. nov.* — MycoBank 809691; Fig. 6

Etymology. Name refers to the District MirpurKhas of Sindh province, Pakistan from where this species was frequently isolated.

Main *hyphae* up to 6 µm wide. *Sporangia* papillate, proliferating, subglobose, limoniform, obovoid or ovoid 20–25 µm diam. Discharge tube short 5–8 × 5–6 µm diam. *Oogonia* large smooth globose, terminal, intercalary, occasionally unilaterally intercalary, (27–)34–37(–40) (av. 34) µm diam. *Antheridia* 1–3 per oogonium, mostly monoclinal or distantly monoclinal, occasionally declinal. Oogonia and antheridial stalk originate from same hyphae. Antheridia apply lengthwise to the oogonium producing lateral or occasionally apical fertilisation tubes. *Oospores* aplerotic or nearly plerotic (22–)29–32(–34) (av. 29.45) µm diam. Oospore wall thickness is 2.5–3 (av. 2.8) µm. *Ooplast* 13–16 µm diam (Fig. 2, 3). Aplerotic index 66.7 %, ooplast index 23 % and wall index 47 %.

Colony characteristics — *Phytophythium mirpureense* produces profuse white cottony growth on PDA and CMDA, on PCA submerged without any patterns, and on CMA with a rosette pattern. The optimum growth occurred at 30 °C. Daily growth at 25 °C on PDA 19 mm, PCA 20 mm, CMA 23.5 mm and CMAD 26 mm. The maximum growth temperature was 35 °C.

Material examined. PAKISTAN, Sindh, District MirpurKhas, MirWah, N25°23' E69°02', stagnant water, 12 Jan. 2006, A.M. Lodhi (holotype CBS 124523, maintained in inactive state. Culture ex-type also deposited as DAOM 238991 in CCFC).

Additional material examined. PAKISTAN, Sindh, from water pond at Sindhri, District MirpurKhas (DAOM 238992, CBS124524) (N25°37' E69°12').

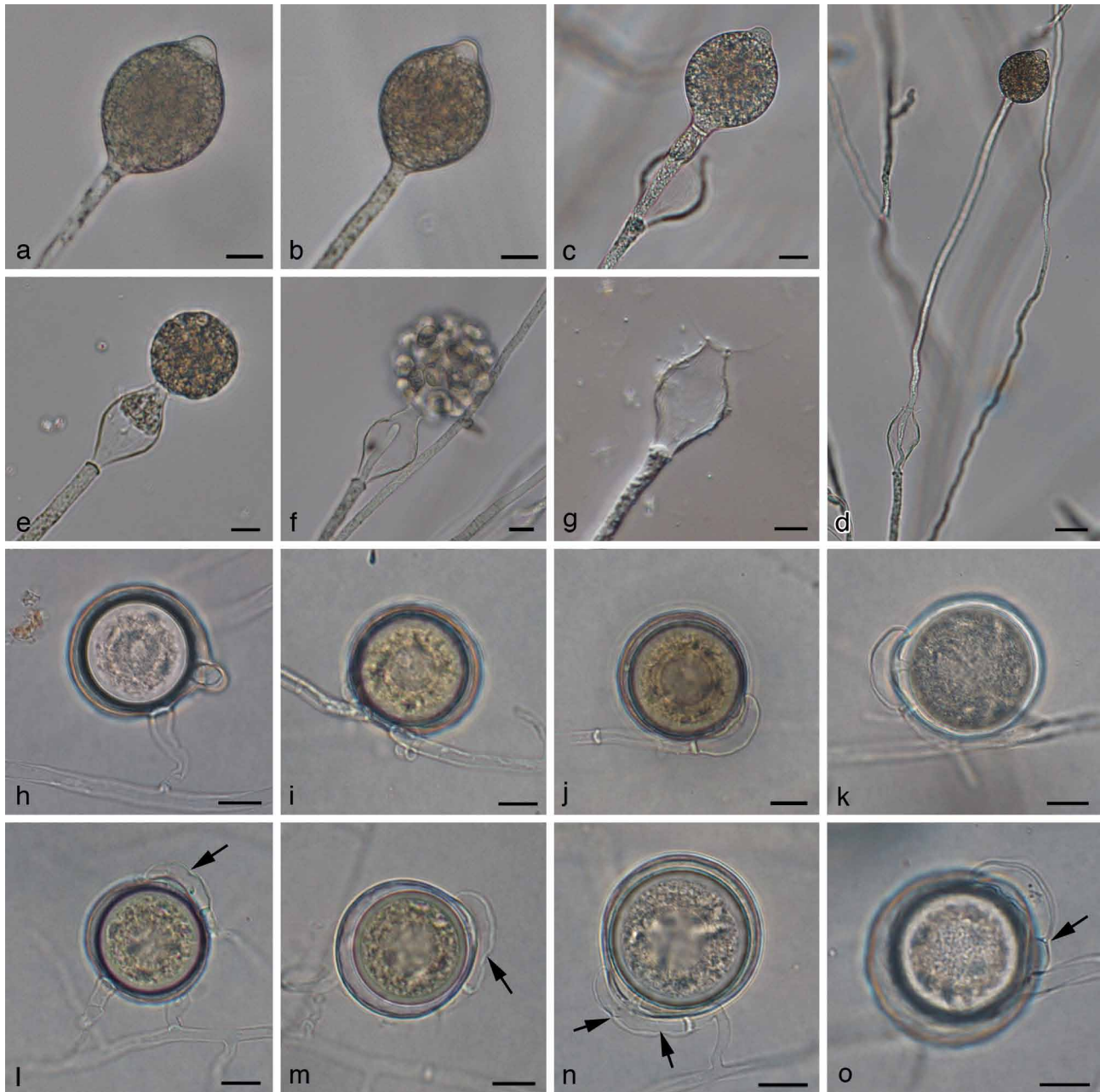


Fig. 6 *Phytophthium mirpurense* sp. nov. sporangia (a–g) and gametangia (h–o). a–b. Papillate sporangia; c. sporangium proliferation outside of empty sporangium; d. internally proliferating sporangium; e. early stage of vesicle formation; f. vesicle with zoospore development inside; g. empty sporangium with remnants of vesicle membrane still attached; h. oogonium on short lateral stalk; i. unilaterally intercalary oogonium; j–o. oogonia with aplerotic oospores and long, cylindrical antheria. Arrows indicate constrictions in antheridia. — Scale bar in all figures 10 µm, except panel d (20 µm).

Acknowledgements We thank Nicole Désaulniers for assistance in maintaining *Phytophthium* cultures, Rafik Assabgui and Julie Chapados from Agriculture and Agri-Food Canada, Ottawa for sequencing these strains. Strains were received from Anne Dorrance from The Ohio State University, Food, Agricultural, and Environmental Sciences, Plant Pathology, Columbus, OH, USA. We thank Marjan Vermaas for composing the photo plates. This research was supported through funding to the Consortium for the Barcode of Life Network (CBOL) from Genome Canada (through the Ontario Genomics Institute), NSERC and other sponsors listed at <http://www.BOLNET.ca>.

REFERENCES

- Bala K, Robideau GP, Désaulniers N, et al. 2010a. Taxonomy, DNA barcoding and phylogeny of three new species of *Pythium* from Canada. *Persoonia* 25: 22–31.
- Bala K, Robideau GP, Lévesque CA, et al. 2010b. *Phytophthium* *Abad*, de Cock, Bala, Robideau, Lodhi & Lévesque, gen. nov. and *Phytophthium* *sindhun* Lodhi, Shahzad & Lévesque, sp. nov. *Fungal Planet* 49. *Persoonia* 24: 136–137.
- Bedard JE, Schurko AM, Cock AWAM de, et al. 2006. Diversity and evolution of 5S rRNA gene family organization in *Pythium*. *Mycological Research* 110: 86–95.
- Blackwell E. 1949. Terminology in *Phytophthora*. *Mycological Papers* 30: 1–24.
- Briard M, Dutertre M, Rouxel F, et al. 1995. Ribosomal RNA sequence divergence within the Pythiaceae. *Mycological Research* 99: 1119–1127.
- Butler EJ. 1907. An account of the genus *Pythium* and some Chytridiaceae. *Memoirs of the Department of Agriculture, Botanical Series* 1: 1–162.
- Cock AWAM de, Lévesque CA. 2004. New species of *Pythium* and *Phytophthora*. *Studies in Mycology* 50: 481–487.
- Cooke DEL, Drenth A, Duncan JM, et al. 2000. A molecular phylogeny of *Phytophthora* and related oomycetes. *Fungal Genetics and Biology* 30: 17–32.
- Crous PW, Gams W, Stalpers JA, et al. 2004. MycoBank: an online initiative to launch mycology into the 21st century. *Studies in Mycology* 50: 19–22.
- Crous PW, Verkley GJM, Groenewald JZ, et al. 2009. *Fungal Biodiversity. CBS Laboratory Manual Series 1*. CBS-KNAW Fungal Biodiversity Centre, The Netherlands.
- Guindon S, Gascuel O. 2003. A simple, fast, and accurate algorithm to estimate large phylogenies by maximum likelihood. *Systematic Biology* 52: 696–704.

- Harvey JV. 1925. A study of the water molds and pythiums occurring in the soil of Chapel Hill. *Journal of the Elisha Mitchell Scientific Society* 41: 151–164.
- Hulvey J, Telle S, Nigrelli L, et al. 2010. Salisapiliaceae – a new family of oomycetes from marsh grass litter of southeastern North America. *Peresoonia* 25: 109–116.
- Hyde KD, Nilsson RH, Alias SA, et al. 2014. One stop shop: backbones trees for important phytopathogenic genera: I. *Fungal Diversity* 67: 21–125.
- Katoh K, Kuma K, Toh H, et al. 2005. MAFFT version 5: improvement in accuracy of multiple sequence alignment. *Nucleic Acids Research* 33: 511–518.
- Lévesque CA, Cock AWAM de. 2004. Molecular phylogeny and taxonomy of the genus *Pythium*. *Mycological Research* 108: 1363–1383.
- Man in 't Veld WA, Cock AWAM de, Ilieva E, et al. 2002. Gene flow analysis of *Phytophthora porri* reveals a new species: *Phytophthora brassicae* sp. nov. *European Journal of Plant Pathology* 108: 51–62.
- Marano AV, Jesus AL, Souza JI de, et al. 2014. A new combination in *Pythium*: *P. kandeliae* (Oomycetes, Straminipila). *Journal of Fungal Biology* 5: 510–522.
- Mazzola M, Andrews PK, Reganold JP, et al. 2002. Frequency, virulence, and metalaxyl sensitivity of *Pythium* spp. isolated from apple roots under conventional and organic production systems. *Plant Disease* 86: 669–675.
- McNeill J, Barrie FR, Buck WR, et al. 2012. International code of nomenclature for algae, fungi and plants (Melbourne code) : adopted by the Eighteenth International Botanical Congress Melbourne, Australia, July 2011. Koeltz Scientific Books, International Association for Plant Taxonomy, Königstein, Germany.
- Plaats-Niterink AJ van der. 1981. Monograph of the genus *Pythium*. *Studies in Mycology* 21: 1–242.
- Posada D. 2008. jModelTest: phylogenetic model averaging. *Molecular Biology and Evolution* 25: 1253–1256.
- Pringsheim, N. 1858. Beiträge zur Morphologie und Systematik der Algen. 2. Die Saprolegnieen. *Jahrbücher für Wissenschaftliche Botanik* 1: 284–306.
- R Development Core Team. 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Robideau GP, Cock AWAM de, Coffey MD, et al. 2011. DNA barcoding of oomycetes with cytochrome c oxidase subunit I and internal transcribed spacer. *Molecular Ecology Resources* 11: 1002–1011.
- Ronquist F, Huelsenbeck JP. 2003. MrBayes 3: Bayesian phylogenetic inference under mixed models. *Bioinformatics (Oxford, England)* 19: 1572–1574.
- Schoch CL, Seifert KA, Huhndorf S, et al. 2012. Nuclear ribosomal internal transcribed spacer (ITS) region as a universal DNA barcode marker for fungi. *Proceedings of the National Academy of Sciences of the United States of America* 109: 6241–6246.
- Schroeder KL, Martin FN, Cock AWAM de, et al. 2013. Molecular detection and quantification of *Pythium* species – evolving taxonomy, new tools and challenges. *Plant Disease* 9: 4–20.
- Shahzad S, Coe R, Dick MW. 1992. Biometry of oospores and oogonia of *Pythium* (Oomycetes): the independent taxonomic value of calculated ratios. *Botanical Journal of the Linnean Society* 108: 143–165.
- Spies CF, Mazzola M, Botha WJ, et al. 2011. Oogonial biometry and phylogenetic analyses of the *Pythium vexans* species group from woody agricultural hosts in South Africa reveal distinct groups within this taxon. *Fungal Biology* 115: 157–168.
- Thines M. 2014. Phylogeny and evolution of plant pathogenic oomycetes – a global overview. *European Journal of Plant Pathology* 138: 431–447.
- Uzughashi S, Tojo M, Kakishima M. 2010. Phylogeny of the genus *Pythium* and description of new genera. *Mycoscience* 51: 337–365.
- Villa NO, Kageyama K, Asano T, et al. 2006. Phylogenetic relationships of *Pythium* and *Phytophthora* species based on ITS rDNA, cytochrome oxidase II and beta-tubulin gene sequences. *Mycologia* 98: 410–422.
- White TJ, Bruns T, Lee S, et al. 1990. Amplification and direct sequencing of fungal ribosomal RNA genes for phylogenetics. In: Innis MA, Gelfand DH, Sninsky JJ, et al. (eds), *PCR protocols, a guide to methods and applications*: 315–322. Academic Press, San Diego.