

# Denaturing gradient gel electrophoresis as a fingerprinting method for the analysis of soil microbial communities

V. Valášková, P. Baldrian

*Laboratory of Environmental Microbiology, Institute of Microbiology of the Academy of Sciences of the Czech Republic, Prague, Czech Republic*

## ABSTRACT

In soil microbial ecology, the effects of environmental factors and their gradients, temporal changes or the response to specific experimental treatments of microbial communities can only be effectively analyzed using methods that address the structural differences among whole communities. Fingerprinting methods are the most appropriate technique for this task when multiple samples must be analyzed. Among the methods currently used to compare microbial communities based on nucleic acid sequences, the techniques based on differences in the melting properties of double-stranded molecules, denaturing gradient gel electrophoresis (DGGE) or temperature gradient gel electrophoresis (TGGE), are the most widely used. Their main advantage is that they provide the possibility to further analyze whole sequences contained in fingerprints using molecular methods. In addition to the analysis of microbial communities based on DNA extracted from soils, DGGE/TGGE can also be used for the assessment of the active part of the community based on the analysis of RNA-derived sequences or for the analysis of sequences of functional genes encoding for proteins involved in important soil processes.

**Keywords:** DGGE; bacteria; fungi; microbial community; soil ecology; TGGE

In the last two decades, the methods used to describe the diversity of microbial communities in soils have undergone a shift from cultivation-based approaches to more comprehensive culture-independent methods. This is of critical importance since only a minor fraction of a soil microbial community can be analyzed using cultivation-dependent techniques. Most recent molecular methods are based on the analysis of nucleic acids extracted from environmental samples. Compared to cloning and sequencing, which is very labor-intensive, time consuming and expensive if several samples are analyzed at a time, the molecular fingerprinting method provides a rapid, simultaneous and reproducible analysis of samples, although with limited resolution (Kowalchuk and Smit 2004, Muyzer et al. 2004, Oros-Sichler et al. 2007). In modern soil ecology, denaturing gradient gel electrophoresis (DGGE) and temperature gradient gel electrophoresis (TGGE) are among the most commonly used methods and they provide several advantages

over other common techniques. Importantly, they allow for the simple follow-up identification of at least the most prominent members of the microbial community. The aim of this paper is to compare the DGGE and TGGE techniques to other fingerprinting methods and to offer recommendations for their use in the analysis of soil bacterial and fungal communities.

## Fingerprinting methods to assess the microbial biodiversity in soils

In order to determine how microbial communities change due to external factors, the rapid, comparative analysis of multiple samples is usually required. Fingerprinting methods are designed to allow for the rapid comparison of samples, identifying any similarities or differences in composition or diversity. None of these techniques, however, are able to identify individual members of the microbial com-

---

Supported by the Czech Science Foundation, Grant No. 526/08/0751, by the Ministry of Education, Youth and Sports of the Czech Republic, Project No. LC06066 and by the Institutional Research Concept of the Institute of Microbiology of the Academy of Sciences of the Czech Republic, Project No. AV0Z50200510.

munity. Most fingerprinting methods are based on molecular biology techniques using isolated DNA or RNA and several employ a polymerase chain reaction (PCR) amplification step followed by electrophoretic separation. One exception is the analysis of phospholipid fatty acids (PLFA), which is based on the molecular fingerprinting of lipid molecules of the microbial membranes. DGGE and TGGE are based on the electrophoretic separation of double stranded DNA molecules based on the differences in their melting behavior in a gradient of either a denaturing agent or temperature. Single-strand conformation polymorphism analysis (SSCP) separates single-stranded DNA molecules based on differences in their secondary structures, while terminal restriction length polymorphism (T-RFLP) detects differences in the localization of restriction sites in DNA sequences. Both length heterogeneity PCR (LH-PCR) and automated ribosomal intergenic spacer analysis (ARISA) separate whole sequences that differ in length. Microarray analysis uses the specific hybridi-

zation of environmental nucleic acids to an array of probes to detect targeted sequences in the sample. For more detailed information on the background of individual methods and their use, see Kowalchuk et al. (2004) and Oros-Sichler et al. (2007).

The most important advantages and disadvantages of individual methods are summarized in Table 1. The main advantage of the PLFA analysis is the ability to assess the diversity of both bacterial and fungal (and with some modifications *Archaea*) communities simultaneously. However, this high coverage is unfortunately contrasted by a very low level of taxonomic discrimination. While an advantage of microarrays is that they can overcome the potential PCR bias, only the part of the community defined by the test probes can be examined. T-RFLP has the highest resolution of the PCR-based methods and can reliably analyze a large number of samples, but a significant portion of the microbial community is inaccessible due to technical exclusion of some of the molecules from the analysis.

Table 1. Common fingerprinting methods used in the analysis of soil microbial communities. See text for the explanation of abbreviations

Method	Advantages	Weaknesses	Reference
DGGE/ TGGE	provides full sequences that can be subject to further analysis	gel-to-gel variation PCR primer design (GC clamp) only short sequences < 400 bp can be analyzed using TGGE	Riesner et al. (1990), Muyzer et al. (1993)
SSCP	provides full sequences that can be subject to further analysis  technically simple gel preparation	complicated DNA preparation (two purification steps)  only short sequences < 200 bp can be analyzed  variant folding of single strand molecules	Lee et al. (1996), Dohrmann and Tebbe (2004)
T-RFLP	technically simple  reproducible  high discrimination power (number of types/analysis)	loss of some variability (sequences not cleaved or cleaved near to primer)  low phylogenetic specificity of terminal restriction sites	Liu et al. (1997)
LH-PCR/ ARISA	technically simple	low discrimination power	Fisher and Triplett (1999)
Microarrays	no bias due to PCR	detects only sequences corresponding to probes  detection limit lower than in PCR-based methods	Shalon et al. (1996)
PLFA analysis	can cover whole communities across kingdoms  quantitative description of the community  no bias due to PCR	low taxonomic separation limited to community composition analysis	Findlay et al. (1989)

## Specificities of DGGE and TGGE analyses

DGGE was originally developed in the 1980s for the identification of point mutations and was first used for the analysis of microbial communities in the early 1990s (Muyzer et al. 1993). The technique separates DNA fragments of the same or similar length but of different sequences by electrophoresis in a gradient of a denaturant. Similar separation principles underlie TGGE, only temperature gradient is used as the denaturant in addition to the chemical compounds in the gel. In the denaturing gradient, DNA fragments migrate under the influence of an electric field. When the fragment reaches a position in the gradient in which it 'melts' (the strands separate), the mobility of the fragment decreases rapidly. In order to prevent complete denaturation of the fragment, a GC clamp – a GC-rich sequence that does not melt – is attached to the 5'-end of one of the primers used in PCR. The GC clamps usually consists of 20–40 bases. The most frequently used GC clamp is the one designed by Muyzer et al. (1993): 5'-CGC CCG CCG CGC CCC GCG CCC GTC CCG CCG CCC CCG CCC G-3'. This clamp is suitable for most applications; however there are several more GC clamps currently in use that differ in their melting properties and are thus suitable for specific conditions (Muyzer et al. 2004).

DGGE analysis provides a picture composed of an array of bands with different intensities. Band intensities correspond to the frequency of individual PCR products in the reaction mixture. Importantly, the excision of selected bands followed by direct reamplification and sequencing can, in some cases, yield a taxonomic identity of the bands. A cloning step before sequencing is usually required in particularly diverse communities where bands can be composed of several sequences or contain background DNA molecules. Alternatively, DGGE gels can be hybridized with taxon-specific probes that can identify one or more bands. In addition to community analysis, DGGE was also successfully used for the analysis of populations of functional genes (Gremion et al. 2004, Sakurai et al. 2007, Warttiainen et al. 2008). There is a resolution limit with this method as only sequences with intensity higher than 0.1–1% of the total intensity can be technically assessed. Depending on band intensities, up to approximately one hundred of bands can be distinguished on a gel. However, this limitation is relative since a comparable limit of detection can be reached using cloning only if several hundreds to thousands of clones are analyzed. Additionally, in DGGE,

the preparation of denaturing gels can result in significant gel-to-gel variations that can make the comparison of large sample sets difficult.

As stated above, TGGE is based on a similar principle as DGGE (Riesner et al. 1990). Temperature gradients are usually generated by a Peltier-based heating/cooling system that can be regulated as required. As in DGGE, the resolution of TGGE is also mostly dependent upon gel size. The advantage of TGGE is that the gels are chemically homogeneous and ready-made gels can be purchased for specific types of equipment, which decreases the variation between gels. Moreover, TGGE analyses are faster, with an electrophoresis step less than 6 h compared to more than 14 h for DGGE. On the other hand, it is often reported that only relatively short fragments (< 400 bp) are generally separated well. Unfortunately, there are no detailed comparisons of DGGE and TGGE currently available. In our experience, however, it is more difficult to achieve a sharp banding pattern with TGGE than with DGGE. This problem may be due to a limited choice of available instrumentation for TGGE compared to DGGE, resulting in lower use. Therefore, DGGE is better suited for the analysis of more diverse populations.

## Methodological considerations

Although perhaps the most critical step in the process, the optimization of the initial soil sampling strategy for fingerprinting methods has attracted little attention. Given the possible gel-to-gel variations in DGGE, it is better to limit the quantity of samples to a number that can be analyzed on a single gel or a few gels. This, however, requires a good sample collection strategy, pooling of samples and their size to obtain nucleic acids from representative soil samples. In the soil environment, especially in the top layers of highly stratified soils, the composition of microbial communities is vertically structured (Kandeler et al. 1999, Baldrian et al. 2008). Changes in microbial community composition occur, even at the centimeter scale within individual soil horizons or among litters of different ages (Fioretto et al. 2000, Šnajdr et al. 2008). There is also a considerable horizontal component of the spatial variability in microbial soil communities at scales of several centimeters to meters (Saetre and Baath 2000, Šnajdr et al. 2008).

The recovery of nucleic acids from soil or litter samples and their quality are of great importance in all fingerprinting methods. Although there are methods proposed to work well with a relatively

wide range of soils, it is difficult to find one method that is the most suitable for all types of soils (Zhou et al. 1996, Griffiths et al. 2004, Korkama-Rajala et al. 2008, Sagova-Mareckova et al. 2008). If sufficient amounts of nucleic acids are available, it is better to limit the number of PCR cycles or to run the PCR in multiple separate reactions to limit the PCR bias.

The sequences of the genes encoding ribosomal RNA or the sequences between these genes attract the most attention. Alternative phylogenetic markers, such as the gene encoding the elongation factor Tu (EF<sub>Tu</sub>) and the gene for the RNA polymerase  $\beta$  subunit (rpoB), have not been commonly used (Oros-Sichler et al. 2007). The preference for rRNA-based markers is mainly due to the fact that these sequences are present in all members of microbial communities and contain both conserved regions suitable for primer design and variable regions allowing the

discrimination between individual microbial taxa (Oros-Sichler et al. 2007). However, there are some difficulties with using the rRNA-based markers that need to be taken into account. Organisms may vary in the copy number of these sequences or multiple different sequences can be present within a single strain, which can result in multiple DGGE bands. In the case of bacteria, the 16S rRNA gene is by far the most frequently used marker and its hypervariable regions V3 (primers 341f-gc/518) and V6-V8 (primers 968gc-1378) of 16S ribosomal DNA (rDNA) are the most commonly used (Table 2).

The primers used for the analysis of fungal communities are more variable and target the 18S or 28S rDNA or the internal transcribed spacers (ITS) 1 or 2 between the rDNA genes (Table 2). The ratio of sequences belonging to Ascomycota, Basidiomycota, Chytridiomycota and Zygomycota is essentially the

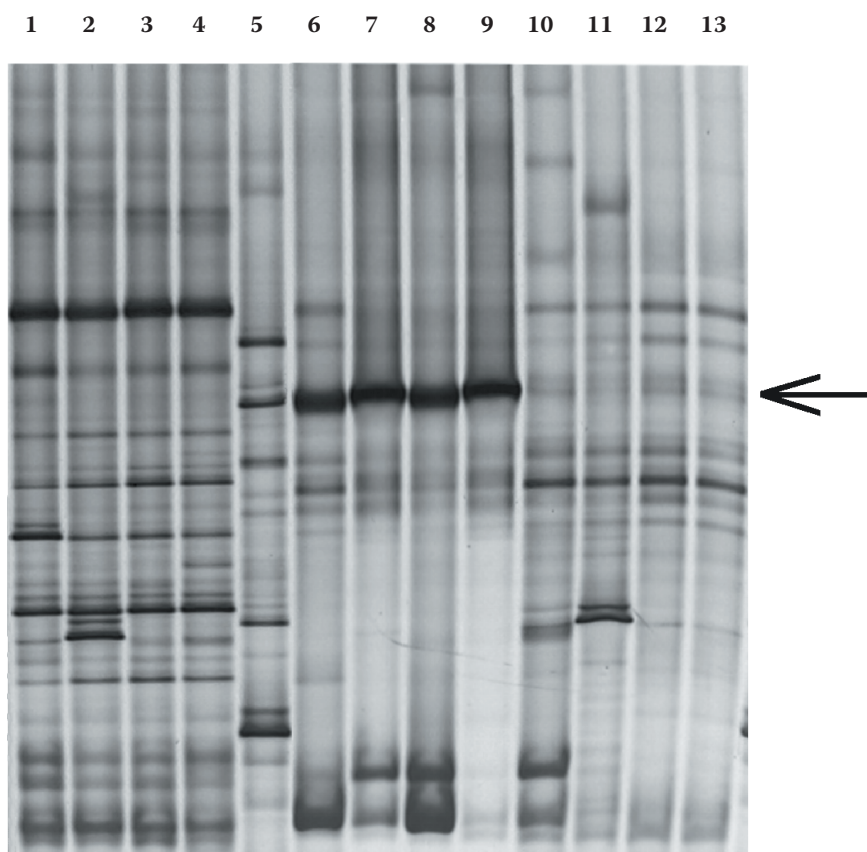


Figure 1. DGGE pattern of ITS1 region of fungal and basidiomycete community in *Quercus* sp. forest litter (Xaverov Natural Reserve near Prague, Czech Republic; Šnajdr et al. (2008)) developed during a 15-week laboratory cultivation in the presence or absence of the mycelia of a saprotrophic basidiomycete *Hypholoma fasciculare* isolated from the same site (Valášková et al. 2007). The DGGE analysis was run using the procedure described in this paper. In order to specifically analyze the fungi belonging to Basidiomycota, the reverse primer ITS4B 5'- CAG GAG ACT TGT ACA CGG TCC AG-3' was used instead of ITS4 in the first round of the nested PCR. From left: lanes 1–4 fungal community in nonsterile leaf litter unaffected by colonization by *H. fasciculare*, lane 5 marker, lanes 6–9 community of basidiomycetes in nonsterile litter colonized by *H. fasciculare*, lanes 10–13 control community of basidiomycetes in nonsterile litter unaffected by colonization of *H. fasciculare*. The thick band in lanes 6–9 indicated by the arrow indicates the band of *H. fasciculare*



Table 2. Overview of the common PCR-DGGE systems used for microbial community analysis in soils

Target group	PCR target sequence	Primer pair	Reference
Bacteria, general	bacterial 16S, V3	341f-gc/518r	Muyzer et al. (1993)
	bacterial 16S, V3-V4	341f-gc/U758	Phillips et al. (2008)
	bacterial 16S, V3-V5	341f/907r-gc	Muyzer et al. (2004)
	bacterial 16S, V6-V8	968-gc/1378	Kozdrój and van Elsas (2001), this paper
	bacterial 16S, V6-V8	968-gc/1401	Heuer and Smala (1997)
Bacteria, alpha-proteobacteria	bacterial 16S, V6-V8	203a f/1492r (or 1494) nested 968-gc/1378	Gelsomino and Cacco (2006)
Bacteria, beta-proteobacteria	bacterial 16S, V6-V8	948b f/1492r (or 1494) nested 968-gc/1378	Gelsomino and Cacco (2006)
	bacterial 16S, V6-V8	968 / 1492r (or 1494) nested 968-gc/1492	Gremion et al. (2004)
Bacteria, Actinobacteria	bacterial 16S, V3	243f/513-gc	Heuer et al. (1997)
	bacterial 16S, V3-V5	S-C-Act-0235-a-S-20-gc/ S-C-Act-0878-a-A-19	Jaatinen et al. (2008)
	bacterial 16S, V6-V8	243f/1492r (or 1494) nested 968-gc/1378	Gelsomino and Cacco (2006)
Bacteria, Pseudomonads	bacterial 16S, V3	Psf/1378 nested 341-gc/518r	Yao et al. (2006)
Bacteria, ammonia oxidizers	bacterial 16S, V2-V4	63f/1378r nested (CTO189fA/B-gc and CTO189fC-gc)/CTO654r	Ros et al. (2006)
	bacterial 16S, V2-V4	(CTO189fA/B-GC and CTO189fC-GC)/CTO654r	Kowalchuk et al. (1998)
Fungi, general	fungus 18S	NS1/Fung-gc	Möhlenhoff et al. (2001)
	fungus 18S	EF390/FR1-gc	Vainio and Hantula (2000)
	fungus 18S	NS1/FR1-gc	Vainio and Hantula (2000)
	fungus 18S	NS1/EF3 nested NS1/FR1-gc	Oros-Sichler et al. (2006)
	fungus 18S	EF4/EF3 nested EF4/Fung5-gc	van Elsas et al. (2000)
	fungus 18S	EF4/EF3 nested NS2/Fung5-gc	van Elsas et al. (2000)
	fungus 18S	EF4/EF3 nested EF4/NS2-gc	van Elsas et al. (2000)
	fungus 18S	EF4/EF3 nested nu-ssu0817/NS4-gc	Bastias et al. (2007)
	fungus 18S	EF4/EF3 nested EF4/NS3-gc	Smit et al. (1999)
	fungus 18S	NS1-gc/NS2	Kowalchuk et al. (1997)
	fungus 18S	EF4/Fung5 nested NS2/Fung5-gc	Clegg (2006)
	fungus 28S	403f/662r-gc	Diouf et al. (2006)
	fungus 28S	NL359/NL912-gc	Zuccaro et al. (2003)
	fungus ITS	ITS1f/ITS4 nested ITS1f-gc/ITS2	Anderson et al. (2003)
	fungus ITS	ITS1f-gc/ITS2	Bougoure and Cairney (2005)
	fungus ITS	ITS1/ITS2-gc	Yao et al. (2006)
	fungus ITS	ITS3/ITS4-gc	Arenz et al. (2006)
Fungi, Ascomycota	fungus ITS	ITS1/ITS4A nested ITS1/ITS2-gc	Larena et al. (1999), Yao et al. (2006)
Fungi, Basidiomycota	fungus ITS	ITS1f/ITS4B-gc	Kowalchuk and Smit (2004)
	fungus ITS	ITS1/ITS4B nested ITS1/ITS2-gc	White et al. (1990), Yao et al. (2006)
Fungi, Basidiomycota	fungus ITS	ITS1/ITS4B nested ITS1f-gc/ITS2	this paper
Fungi, arbuscular mycorrhiza	fungus 18S	AM1/NS31-gc	Kowalchuk et al. (2002)

same for the 18S- and ITS-based primers (Anderson et al. 2003). However, it is generally accepted that the ITS region is preferred due to its higher variability. The identification of fungi using the 18S rRNA sequence is usually limited to genus or family in Ascomycota and Basidiomycota, although it can be useful for the discrimination of Glomeromycota. The ITS sequences are species-specific for most fungi (Anderson and Cairney 2004, Kowalchuk and Smit 2004). However, even the ITS regions are not variable enough to discriminate some fungal species, like *Penicillium* spp., where beta-tubulin or cytochrome oxidase genes are used for taxonomy instead (Seifert et al. 2007).

Previous studies on soil microbial diversity demonstrated that soil can contain tens of thousands of bacterial species per gram of soil, with different levels of community evenness (Roesch et al. 2007). Thus, this is not surprising that the molecular fingerprints of such communities may result in a very complex fingerprint patterns. Using DGGE, this is represented by many equally intense bands and sometimes even by a smear with no clear resolution of individual bands. To overcome these difficulties, individual subgroups of bacterial or fungal communities can be targeted specifically (Tables 2 and 3). In this paper, we demonstrate a nested PCR procedure that is able to show on a single gel both the whole fungal community and the subcommunity of fungi belonging to Basidiomycota, where the localization of individual bands corresponds between the two communities (Figure 1).

DNA is the most generally used molecule in molecular fingerprinting methods. However, after extraction from soil or litter and reverse transcription, RNA-based communities can also be analyzed. This led to the idea that ribosomal RNA (rRNA) molecules extracted from the environment could be a good tool for studying active members of microbial communities due to the fact that each molecule represents one ribosome copy and cell activity (growth rate) is coupled to an increase in ribosomes (Rosset et al. 1966). Several studies on bacteria and fungi in soil or litter demonstrated that active populations are formed by a subset of species present in the total residential community (Duineveld et al. 2001, Aneja et al. 2004, Pennanen et al. 2004). While this seems to be a useful approach for functional studies, the presence of copious ribosomes in some resting spores of fungi and bacteria can make it less exact. Currently, the analysis of the whole ribosomal RNA transcripts containing both the rRNA genes and ITS in soil and litter was shown to work well for the analysis of fungal communities (Korkama-Rajala et

al. 2008). Since the turnover of these molecules is rapid, this is probably the best method to analyze the active fungal community.

Once the DGGE fingerprint is obtained, there are several statistical methods available to analyze the community variability or similarity of samples. The most important decision in the analysis is whether just the presence or absence of bands or their intensities should be used. The latter approach should be selected with great caution and only in the case that all bands on a gel contain the same amount of DNA. For more information on classical fingerprint processing techniques, please refer to Oros-Sichler et al. (2007). Alternatively, DGGE can be followed by cutting and reamplification of individual (usually dominant) bands, which can be later cloned and sequenced to reveal the identity of the most prominent members of the community (Muyzer et al. 2004). This approach was found to work well in several cases, but can be only used for a relatively limited number of bands per sample.

## Recommended procedures

The following procedures were used to successfully characterize bacterial and fungal communities in soils (Heuer and Smala 1997, Kozdrój and van Elsas 2001, Anderson et al. 2003, Marschner et al. 2003, Hernesmaa et al. 2005, Artz et al. 2007). The procedures target particularly variable parts of the respective rDNA regions (see above) and result in rich banding patterns that are suitable for subsequent sequence analysis and taxonomic identification of corresponding bacteria or fungi.

**Bacterial community analysis.** The forward primer 968-gc 5'-CGC CCG GGG CGC GCC CCG GGC GGG GCG GGG GCA CGG GGG GAA CGC GAA GAA CCT TAC-3' and the reverse primer 1378 5'-CGG TGT GTA CAA GGC CCG GGA ACG-3' are used. These primers target the V6-V8 hypervariable region of bacterial 16S rDNA (Table 3).

The PCR reaction consists of 1 × PCR buffer with MgCl<sub>2</sub>, 100 μM dNTPs, 20 pmol forward primer, 20 pmol reverse primer, 3 U DNA polymerase (e.g. Dynazyme II, Finnzymes), 1–2 μl DNA (50 ng/μl) template and H<sub>2</sub>O to bring the volume to 50 μl. The amplification yield of soil samples can be improved by the addition of 30 μg of bovine serum albumin per 50 μl reaction. Cycling conditions: 94°C for 2 min, 35 cycles (92°C for 30 s, 55°C for 1 min, 72°C for 45 s + 1 s/cycle) and 72°C for 5 min. The PCR product quality is tested on 1.5% (w/v) agarose gels and the size of PCR products is

Table 3. PCR primers used for DGGE/TGGE microbial community analysis in soils

PCR target	Primer	Sequence 5' to 3'	Primer position	Reference
Bacterial 16S	513	CGGCCGCGGCTGCTGGCACGTA	16S-513	Heuer et al. (1997)
	1378r	CGGTGTGTACAAGGCCCGGGAACG	16S-1378	Heuer and Smala (1997)
	1401r	CGGTGTGTACAAGACCC	16S-1401	Heuer and Smala (1997)
	1492r	TACGGYTACCTTGTTACGACTT	16S-1492	Heuer and Smala (1997)
	1494r	CTACGGYTACCTTGTTACGAC	16S-1494	Gremion et al. (2004)
	203a f	CCGCATACGCCCTACGGGGGAAAGA TTTAT	16S-203	Gelsomino and Cacco (2006)
	243f	GGATGAGCCCCGCGGCCTA	16S-243	Heuer et al. (1997)
	341f	CCTACGGGAGGCAGCAG	16S-341	Muyzer et al. (1993)
	518r	ATTACCGCGGCTGCTGG	16S-518	Muyzer et al. (1993)
	63f	CAGGCCTAACACATGCAAGTC	16S-63	Ros et al. (2006)
	907r	CCGTCAATTCCTTTGAGTTT	16S-907	Muyzer et al. (1995)
	948b f	CGCACAAGCGGTGGATGA	16S-948	Gelsomino and Cacco (2006)
	968f	AACGCGAAGAACCTTAC	16S-968	Felske et al. (1996)
	CTO189fA/B	GGAGRAAAGCAGGGGATCG	16S-189	Kowalchuk et al. (1998)
	CTO189fC	GGAGGAAAGTAGGGGATCG	16S-189	Kowalchuk et al. (1998)
	CTO654r	CTAGCYTTGTAGTTTCAAACGC	16S-654	Kowalchuk et al. (1998)
	P27f	GAGTTTGATCCTGGCTCAG	16S-27	Heuer and Smala (1997)
	Psf	GGTCTGAGAGGATGATCAGT		Yao et al. (2006)
	S-C-Act-0235-a-S-20	CGCGGCCTATCAGCTTGTTG	16S-235	Jaatinen et al. (2008)
	S-C-Act-878-a-A-19	CCGTACTCCCCAGGCGGGG	16S-878	Jaatinen et al. (2008)
Fungal 18S	U758	CTACCAGGGTATCTAATCC	16S-758	Phillips et al. (2008)
	AM1	GTTTCCCGTAAGGCGCCGAA		Santos et al. (2006)
	EF3	TCCTCTAAATGACCAGTTTG	18S-195	Smit et al. (1999)
	EF4	GGAAGGGRTGTATTTATTAG	18S-573	Smit et al. (1999)
	EF390	CGATAACGAACGAGACCT	18S-1317	Vainio and Hantula (2000)
	FR1	AICCATTC AATCGGTAIT	18S-1664	Vainio and Hantula (2000)
	Fung	ATTCCCCGTTACCCGTTG	18S-368	May et al. (2001)
	Fung5	GTAAAAGTCCTGGTTCCCC	18S-747	Smit et al. (1999)
	NS1	GTAGTCATATGCTTGCTCTC	18S-17	White et al. (1990)
	NS2	GGCTGCTGGCACCAGACTTGC	18S-337	White et al. (1990)
	NS3	GCAAGTCTGGTGCCAGCAGCC	18S-573	White et al. (1990)
	NS31	TTGGAGGGCAAGTCTGGTGCC		Santos et al. (2006)
	NS4	CTTCCGTCAATTCCTTTAAG	18S-1131	White et al. (1990)
	nu-ssu0817	TTAGCATGGAATAATRR AATAGGA	18S-817	Bastias et al. (2007)
Fungal 28S	403f	GTGAAATTGTTGAAAGGGAA	28S-403	Diouf et al. (2006)
	662r	GACTCCTTGGTCCGTGTT	28S-662	Diouf et al. (2006)
	NL359	GGACGCCATAGAGGGTGAGAGC	28S-359	Zuccaro et al. (2003)
	NL912	TCAAATCCATCCGAGAACATCAG	28S-912	Zuccaro et al. (2003)
Fungal ITS	ITS1	TCCGTAGGTGAACCTGCGG	18S-1787	White et al. (1990)
	ITS1f	CTTGGTCATTTAGAGGAAGTAA		Gardes and Bruns (1993)
	ITS2	GCTGCGTTCTTCATCGATGC		White et al. (1990)
	ITS3	GCATCGATGAAGAACGCAGC		White et al. (1990)
	ITS4	TCCTCCGCTTATTGATATGC	28S-41	White et al. (1990)
	ITS4A	CGCCGTTACTGGGGCAATCCCTG		Larena et al. (1999)
	ITS4B	CAGGAGACTTGTACACGGTCCAG		Gardes and Bruns (1993)

approximately 500 bp. The DNA samples (0.5 µg DNA/lane for a rich bacterial community) are mixed with a loading dye (e.g., the DNA loading dye from Fermentas) 4:1 prior to application.

The gel solution consists of 6% (w/v) acrylamide/bisacrylamide (37.5:1), in 0.5 × TAE buffer, pH 8.3, containing 55% to 61% of the denaturant (100% denaturant consists of 7M urea and 40% formamide). The stacking gel consists of 6% acrylamide/bisacrylamide (37.5:1) and 0.5 × TAE buffer, pH 8.3. The gels are prepared, loaded and run according to the instructions of the manufacturers of individual DGGE systems (e.g., D-Code, BioRad or PhorU 2 × 2, Ingeny). The typical time of separation proceeds for 17 h at 200 V in 0.5 × TAE buffer (60°C). The gels can be stained with ethidium bromide (EtBr), Gel Star, SYBR Green or silver stained. For EtBr staining, the gels should be immersed for 15 min in an EtBr bath (50 µl of 1% EtBr per l of H<sub>2</sub>O) and the background reduced by destaining for 15 min in water.

**Fungal community analysis.** The forward primers ITS1f 5'-CTT GGT CAT TTA GAG GAA GTA A-3' and ITS1f-gc 5'-CGC CCG CCG CGC GCG GCG GGC GGG GCG GGG GCA CGG GGG GCT TGG TCA TTT AGA GGA AGT AA-3' and the reverse primers ITS2 5'-GCT GCG TTC TTC ATC GAT GC-3' and ITS4 5'-TCC TCC GCT TAT TGA TAT GC-3' are used (Table 3).

Nested PCR is used for the amplification of the ITS1 region of fungal rDNA. A fragment comprising both ITS1 and ITS2 is amplified in the first PCR reaction using the primer pair ITS1f/ITS4. After the purification of the PCR product, the ITS1 region is specifically amplified in the second PCR reaction using the ITS1f-gc/ITS2 primers.

The first PCR reaction consists of 1 × PCR buffer with MgCl<sub>2</sub>, 100µM dNTPs, 10 pmol ITS1f primer, 10 pmol ITS4 primer, 1.5 U DNA polymerase, 1 µl DNA template (50 ng/µl) and H<sub>2</sub>O to bring the volume to 25 µl. The amplification yield of soil samples can be improved by the addition of 15 µg of bovine serum albumin per 30 µl reaction. Cycling conditions: 94°C for 5 min, 35 cycles (94°C for 1 min, 50°C for 1 min, 72°C for 1 min) and 72°C for 10 min. The size of PCR products is approximately 700–900 bp.

The second PCR reaction consists of 1 × PCR buffer with MgCl<sub>2</sub>, 200µM dNTPs, 20 pmol ITS1f-gc primer, 20 pmol ITS2 primer, 3 U DNA polymerase, 1 µl of PCR product from the first PCR as a template and H<sub>2</sub>O to bring the volume to 50 µl. Cycling conditions: 94°C for 5 min, 35 cycles (94°C for 30 s, 55°C for 30 s, 72°C for 30 s) and 72°C for 10 min. The size of the PCR product is approximately 400 bp. The

DNA samples (0.5 µg DNA/lane for a rich bacterial community) are mixed with a loading dye (e.g., the DNA loading dye from Fermentas) 4:1 prior to application. The DGGE gel is prepared and run as described for analysis of bacterial 16S rDNA with two differences: 9% (w/v) of acrylamide/bisacrylamide is used with a linear gradient of denaturant between 36% and 44%.

#### **General recommendations for DGGE analysis.**

The amount of DNA should reflect the number of expected bands in the fingerprint: the more bands expected the higher amount of DNA should be used. When numbers of bands differ widely between samples, always use the same amount of DNA per electrophoresis lane. Markers should always be used to reduce the effect of minor gel defects (e.g., the 'smiling' effect) or to allow between-gel comparisons. The use of at least three marker lanes per gel is recommended. Markers can easily be derived from environmental samples by cutting and reamplification of 7–10 selected bands. These should preferably be evenly spaced and cover the whole separation area of the gel. If possible, the outer lanes of the gel are better left empty, as the smiling effect may distort the banding pattern. When establishing a DGGE analysis protocol in an experiment with newly designed primers, it is wise to test a broad denaturant gradient in the first trial and to estimate a suitable focused gradient after analyzing the separation results.

The main advantage of DGGE or TGGE is the fact that it offers the possibility to further analyze fingerprints by molecular methods and DGGE is today probably the most commonly used method for typing and comparing microbial communities. In the future, the value of this method can be further increased when suitable primers are developed to address underexplored microbial taxa or functional genes.

#### **REFERENCES**

- Anderson I.C., Cairney J.W.G. (2004): Diversity and ecology of soil fungal communities: increased understanding through the application of molecular techniques. *Environmental Microbiology*, 6: 769–779.
- Anderson I.C., Campbell C.D., Prosser J.I. (2003): Diversity of fungi in organic soils under a moorland – Scots pine (*Pinus sylvestris* L.) gradient. *Environmental Microbiology*, 5: 1121–1132.
- Aneja M.K., Sharma S., Munch J.C., Schlöter M. (2004): RNA fingerprinting – a new method to screen for differences in plant litter degrading microbial communities. *Journal of Microbiological Methods*, 59: 223–231.



- Arenz B.E., Held B.W., Jurgens J.A., Farrell R.L., Blanchette R.A. (2006): Fungal diversity in soils and historic wood from the Ross Sea Region of Antarctica. *Soil Biology and Biochemistry*, 38: 3057–3064.
- Artz R.R.E., Anderson I.C., Chapman S.J., Hagn A., Schloter M., Potts J.M., Campbell C.D. (2007): Changes in fungal community composition in response to vegetational succession during the natural regeneration of cutover peatlands. *Microbial Ecology*, 54: 508–522.
- Baldrian P., Trögl J., Frouz J., Šnajdr J., Valášková V., Merhautová V., Cajthaml T., Herinková J. (2008): Enzyme activities and microbial biomass in topsoil layer during spontaneous succession in spoil heaps after brown coal mining. *Soil Biology and Biochemistry*, 40: 2107–2115.
- Bastias B.A., Anderson I.C., Xu Z., Cairney J.W.G. (2007): RNA- and DNA-based profiling of soil fungal communities in a native Australian eucalypt forest and adjacent *Pinus elliotti* plantation. *Soil Biology and Biochemistry*, 39: 3108–3114.
- Bougoure D.S., Cairney J.W.G. (2005): Fungi associated with hair roots of *Rhododendron lochiaie* (Ericaceae) in an Australian tropical cloud forest revealed by culturing and culture-independent molecular methods. *Environmental Microbiology*, 7: 1743–1754.
- Clegg C.D. (2006): Impact of cattle grazing and inorganic fertiliser additions to managed grasslands on the microbial community composition of soils. *Applied Soil Ecology*, 31: 73–82.
- Diouf M., Miambi E., Mora P., Delgarde S., Rouland C. (2006): The impact of termite sheetings age on their fungal communities. *European Journal of Soil Biology*, 42: 85–91.
- Dohrmann A.B., Tebbe C.C. (2004): Microbial community analysis by PCR-single-strand conformation polymorphism (PCR-SSCP). In: Kowalchuk G.A., de Bruijn F.J., Head I.M., Akkermans A.D.L., van Elsas J.D. (eds): *Molecular Microbial Ecology Manual*. Kluwer Academic Publishers, Dordrecht, 809–838.
- Duineveld B.M., Kowalchuk G.A., Keijzer A., van Elsas J.D., van Veen J.A. (2001): Analysis of bacterial communities in the rhizosphere of chrysanthemum via denaturing gradient gel electrophoresis of PCR-amplified 16S rRNA as well as DNA fragments coding for 16S rRNA. *Applied and Environmental Microbiology*, 67: 172–178.
- Felske A., Engelen B., Nübel U., Backhaus H. (1996): Direct ribosome isolation from soil to extract bacterial rRNA for community analysis. *Applied and Environmental Microbiology*, 62: 3034–3036.
- Findlay R.H., King G.M., Watling L. (1989): Efficacy of phospholipid analysis in determining microbial biomass in sediments. *Applied and Environmental Microbiology*, 55: 2888–2893.
- Fioretto A., Papa S., Curcio E., Sorrentino G., Fuggi A. (2000): Enzyme dynamics on decomposing leaf litter of *Cistus incanus* and *Myrtus communis* in a Mediterranean ecosystem. *Soil Biology and Biochemistry*, 32: 1847–1855.
- Fisher M.M., Triplett E.W. (1999): Automated approach for ribosomal intergenic spacer analysis of microbial diversity and its application to freshwater bacterial communities. *Applied and Environmental Microbiology*, 65: 4630–4636.
- Gardes M., Bruns T.D. (1993): ITS primers with enhanced specificity for basidiomycetes – application to the identification of mycorrhizae and rusts. *Molecular Ecology*, 2: 113–118.
- Gelsomino A., Cacco G. (2006): Compositional shifts of bacterial groups in a solarized and amended soil as determined by denaturing gradient gel electrophoresis. *Soil Biology and Biochemistry*, 38: 91–102.
- Gremion F., Chatzinotas A., Kaufmann K., Von Sigler W., Harms H. (2004): Impacts of heavy metal contamination and phytoremediation on a microbial community during a twelve-month microcosm experiment. *FEMS Microbiology Ecology*, 48: 273–283.
- Griffiths R.I., Manefield M., Whiteley A.S., Bailey M.J. (2004): DNA and RNA extraction from soil. In: Kowalchuk G.A., de Bruijn F.J., Head I.M., Akkermans A.D.L., van Elsas J.D. (eds): *Molecular Microbial Ecology Manual*. Kluwer Academic Publishers, Dordrecht, 149–158.
- Hernesmaa A., Björklöf K., Kiikkilä O., Fritze H., Haahtela K., Romantschuk M. (2005): Structure and function of microbial communities in the rhizosphere of Scots pine after tree-felling. *Soil Biology and Biochemistry*, 37: 777–785.
- Heuer H., Smala K. (1997): Application of denaturing gradient gel electrophoresis (DGGE) and temperature gradient gel electrophoresis (TGGE) for studying soil microbial communities. In: van Elsas J.D., Wellington E.M.H., Trevors J.T. (eds): *Modern Soil Microbiology*. Marcel Dekker New York, 353–373.
- Heuer H., Krsek M., Baker P., Smalla K., Wellington E.M.H. (1997): Analysis of actinomycete communities by specific amplification of genes encoding 16S rRNA and gel-electrophoretic separation in denaturing gradients. *Applied and Environmental Microbiology*, 63: 3233–3241.
- Jaatinen K., Laiho R., Vuorenmaa A., del Castillo U., Minkinen K., Pennanen T., Penttilä T., Fritze H. (2008): Responses of aerobic microbial communities and soil respiration to water-level drawdown in a northern boreal fen. *Environmental Microbiology*, 10: 339–353.
- Kandeler E., Tschirko D., Spiegel H. (1999): Long-term monitoring of microbial biomass, N mineralization

- and enzyme activities of a Chernozem under different tillage management. *Biology and Fertility of Soils*, 28: 343–351.
- Korkama-Rajala T., Mueller M.M., Pennanen T. (2008): Decomposition and fungi of needle litter from slow- and fast-growing norway spruce (*Picea abies*) clones. *Microbial Ecology*, 56: 76–89.
- Kowalchuk G.A., Smit E. (2004): Fungal community analysis using PCR-denaturing gradient gel electrophoresis (DGGE). In: Kowalchuk G.A., de Bruijn F.J., Head I.M., Akkermans A.D.L., van Elsas J.D. (eds): *Molecular Microbial Ecology Manual*. Kluwer Academic Publishers, Dordrecht, 771–788.
- Kowalchuk G.A., Gerards S., Woldendorp J.W. (1997): Detection and characterization of fungal infections of *Ammophila arenaria* (marram grass) roots by denaturing gradient gel electrophoresis of specifically amplified 18S rDNA. *Applied and Environmental Microbiology*, 63: 3858–3865.
- Kowalchuk G.A., de Souza F.A., van Veen J.A. (2002): Community analysis of arbuscular mycorrhizal fungi associated with *Ammophila arenaria* in Dutch coastal sand dunes. *Molecular Ecology*, 11: 571–581.
- Kowalchuk G.A., Bodelier P.L.E., Heilig G.H.J., Stephen J.R., Laanbroek H.J. (1998): Community analysis of ammonia-oxidising bacteria, in relation to oxygen availability in soils and root-oxygenated sediments, using PCR, DGGE and oligonucleotide probe hybridisation. *FEMS Microbiology Ecology*, 27: 339–350.
- Kowalchuk G.A., de Bruijn F.J., Head I.M., Akkermans A.D., van Elsas J.D. (eds.) (2004): *Molecular Microbial Ecology Manual*. Kluwer Academic Publishers, Dordrecht.
- Kozdrój J., van Elsas J.D. (2001): Structural diversity of microbial communities in arable soils of a heavily industrialised area determined by PCR-DGGE fingerprinting and FAME profiling. *Applied Soil Ecology*, 17: 31–42.
- Larena I., Salazar O., Gonzalez V., Julian M.C., Rubio V. (1999): Design of a primer for ribosomal DNA internal transcribed spacer with enhanced specificity for ascomycetes. *Journal of Biotechnology*, 75: 187–194.
- Lee D.H., Zo Y.G., Kim S.J. (1996): Nonradioactive method to study genetic profiles of natural bacterial communities by PCR-single-strand-conformation polymorphism. *Applied and Environmental Microbiology*, 62: 3112–3120.
- Liu W.T., Marsh T.L., Cheng H., Forney L.J. (1997): Characterization of microbial diversity by determining terminal restriction fragment length polymorphisms of genes encoding 16S rRNA. *Applied and Environmental Microbiology*, 63: 4516–4522.
- Marschner P., Kandeler E., Marschner B. (2003): Structure and function of the soil microbial community in a long-term fertilizer experiment. *Soil Biology and Biochemistry*, 35: 453–461.
- May L.A., Smiley B., Schmidt M.G. (2001): Comparative denaturing gradient gel electrophoresis analysis of fungal communities associated with whole plant corn silage. *Canadian Journal of Microbiology*, 47: 829–841.
- Möhlenhoff P., Muller L., Gorbushina A.A., Petersen K. (2001): Molecular approach to the characterisation of fungal communities: methods for DNA extraction, PCR amplification and DGGE analysis of painted art objects. *FEMS Microbiology Letters*, 195: 169–173.
- Muyzer G., de Waal E.C., Uitterlinden A.G. (1993): Profiling of complex microbial populations by denaturing gradient gel electrophoresis analysis of polymerase chain reaction-amplified genes coding for 16S ribosomal RNA. *Applied and Environmental Microbiology*, 59: 695–700.
- Muyzer G., Teske A., Wirsén C.O., Jannasch H.W. (1995): Phylogenetic relationships of *Thiomicrospira* species and their identification in deep-sea hydrothermal vent samples by denaturing gradient gel electrophoresis of 16S rDNA fragments. *Archives of Microbiology*, 164: 165–171.
- Muyzer G., Brinkhoff T., Nubel U., Santegoeds C., Schafer H., Wawer C. (2004): Denaturing gradient gel electrophoresis (DGGE) in microbial ecology. In: Kowalchuk G.A., de Bruijn F.J., Head I.M., Akkermans A.D.L., van Elsas J.D. (eds): *Molecular Microbial Ecology Manual*. Kluwer Academic Publishers Dordrecht, 743–769.
- Oros-Sichler M., Gomes N.C.M., Neuber G., Smalla K. (2006): A new semi-nested PCR protocol to amplify large 18S rRNA gene fragments for PCR-DGGE analysis of soil fungal communities. *Journal of Microbiological Methods*, 65: 63–75.
- Oros-Sichler M., Costa R., Heuer H., Smalla K. (2007): Molecular Fingerprinting Techniques to Analyze Soil Microbial Communities. In: van Elsas J.D., Jansson J.K., Trevors J.T. (eds): *Modern Soil Microbiology*. CRC Press Madison, 355–386.
- Pennanen T., Caul S., Daniell T.J., Griffiths B.S., Ritz K., Wheatley R.E. (2004): Community-level responses of metabolically-active soil microorganisms to the quantity and quality of substrate inputs. *Soil Biology and Biochemistry*, 36: 841–848.
- Phillips L.A., Germida J.J., Farrell R.E., Greer C.W. (2008): Hydrocarbon degradation potential and activity of endophytic bacteria associated with prairie plants. *Soil Biology and Biochemistry*, 40: 3054–3064.
- Riesner D., Henco K., Steger G. (1990): Temperature-Gradient Gel Electrophoresis: A method for the analysis of conformational transitions and mutations in nucleic acids and protein. In: Chrambach A., Dunn M.J., Rado B.J. (eds): *Advances in Electrophoresis*, Vol. 4. VCH Verlagsgesellschaft, Weinheim, 169–250.

- Roesch L.F., Fulthorpe R.R., Riva A., Casella G., Hadwin A.K.M., Kent A.D., Daroub S.H., Camargo F.A.O., Farmerie W.G., Triplett E.W. (2007): Pyrosequencing enumerates and contrasts soil microbial diversity. *International Society for Microbial Ecology Journal*, 1: 283–290.
- Ros M., Pascual J.A., Garcia C., Hernandez M.T., Insam H. (2006): Hydrolase activities, microbial biomass and bacterial community in a soil after long-term amendment with different composts. *Soil Biology and Biochemistry*, 38: 3443–3452.
- Rosset R., Julien J., Monier R. (1966): Ribonucleic acid composition of bacteria as a function of growth rate. *Journal of Molecular Biology*, 18: 308–320.
- Saetre P., Baath E. (2000): Spatial variation and patterns of soil microbial community structure in a mixed spruce-birch stand. *Soil Biology and Biochemistry*, 32: 909–917.
- Sagova-Mareckova M., Cermak L., Novotna J., Plhachova K., Forstova J., Kopecky J. (2008): Innovative methods for soil DNA purification tested in soils with widely differing characteristics. *Applied and Environmental Microbiology*, 74: 2902–2907.
- Sakurai M., Suzuki K., Onodera M., Shinano T., Osaki M. (2007): Analysis of bacterial communities in soil by PCR-DGGE targeting protease genes. *Soil Biology and Biochemistry*, 39: 2777–2784.
- Santos J.C., Finlay R.D., Tehler A. (2006): Molecular analysis of arbuscular mycorrhizal fungi colonising a semi-natural grassland along a fertilisation gradient. *New Phytologist*, 172: 159–168.
- Seifert K.A., Samson R.A., Dewaard J.R., Houbraeken J., Levesque C.A., Moncalvo J.M., Louis-Seize G., Hebert P.D.N. (2007): Prospects for fungus identification using CO1 DNA barcodes, with *Penicillium* as a test case. *Proceedings of the National Academy of Sciences of the United States of America*, 104: 3901–3906.
- Shalon D., Smith S.J., Brown P.O. (1996): A DNA microarray system for analyzing complex DNA samples using two-color fluorescent probe hybridization. *Genome Research*, 6: 639–645.
- Smit E., Leeflang P., Glandorf B., van Elsas J.D., Wernars K. (1999): Analysis of fungal diversity in the wheat rhizosphere by sequencing of cloned PCR-amplified genes encoding 18S rRNA and temperature gradient gel electrophoresis. *Applied and Environmental Microbiology*, 65: 2614–2621.
- Šnajdr J., Valášková V., Merhautová V., Herinková J., Cajthaml T., Baldrian P. (2008): Spatial variability of enzyme activities and microbial biomass in the upper layers of *Quercus petraea* forest soil. *Soil Biology and Biochemistry*, 40: 2068–2075.
- Vainio E.J., Hantula J. (2000): Direct analysis of wood-inhabiting fungi using denaturing gradient gel electrophoresis of amplified ribosomal DNA. *Mycological Research*, 104: 927–936.
- Valášková V., Šnajdr J., Bittner B., Cajthaml T., Merhautová V., Hofrichter M., Baldrian P. (2007): Production of lignocellulose-degrading enzymes and degradation of leaf litter by saprotrophic basidiomycetes isolated from a *Quercus petraea* forest. *Soil Biology and Biochemistry*, 39: 2651–2660.
- van Elsas J.D., Duarte G.F., Keijzer-Wolters A., Smit E. (2000): Analysis of the dynamics of fungal communities in soil via fungal-specific PCR of soil DNA followed by denaturing gradient gel electrophoresis. *Journal of Microbiological Methods*, 43: 133–151.
- Wartiainen I., Eriksson T., Zheng W., Rasmussen U. (2008): Variation in the active diazotrophic community in rice paddy-nifH PCR-DGGE analysis of rhizosphere and bulk soil. *Applied Soil Ecology*, 39: 65–75.
- White T.J., Bruns T., Lee S., Taylor J. (1990): Amplification and direct sequencing of fungal ribosomal RNA genes for phylogenetics. In: Innis M.A., Gelfand D.H., Sninsky J.J., White T.J. (eds): *PCR Protocols*. Academic Press San Diego, 315–322.
- Yao S., Merwin I.A., Abawi G.S., Thies J.E. (2006): Soil fumigation and compost amendment alter soil microbial community composition but do not improve tree growth or yield in an apple replant site. *Soil Biology and Biochemistry*, 38: 587–599.
- Zhou J.Z., Bruns M.A., Tiedje J.M. (1996): DNA recovery from soils of diverse composition. *Applied and Environmental Microbiology*, 62: 316–322.
- Zuccaro A., Schulz B., Mitchell J.I. (2003): Molecular detection of ascomycetes associated with *Fucus serratus*. *Mycological Research*, 107: 1451–1466.

Received on July 1, 2009

---

*Corresponding author:*

Dr. Petr Baldrian, Mikrobiologický ústav Akademie věd České Republiky, Vídeňská 1083, 14220 Praha 4, Česká Republika  
e-mail: baldrian@biomed.cas.cz

---