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Source: Applications in Plant Sciences, 2(12)

Published By: Botanical Society of America

URL: <https://doi.org/10.3732/apps.1400093>

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DEVELOPMENT AND CHARACTERIZATION OF NUCLEAR MICROSATELLITE MARKERS IN THE ENDOPHYTIC FUNGUS *EPICHLÖE FESTUCAE* (CLAVICIPITACEAE)¹

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- *Premise of the study:* Microsatellite primers were developed for the endophytic fungus *Epichloë festucae*, which is symbiotic with *Festuca rubra*, to study the population genetics of the species and to compare population structures between *E. festucae* and its host *F. rubra*.
- *Methods and Results:* We developed 14 polymorphic markers using the unplaced genomic scaffold sequences of *E. festucae* from GenBank. The number of alleles per locus (*A*) varied from four to 16, and unbiased haploid diversity (*h*) was 0.717 in eight populations located in the Faroe Islands, Finland, and Spain. The Spanish populations possessed a higher number of alleles and haploid diversity (on average *A* = 5.1 and *h* = 0.591, respectively) compared to northern populations (on average *A* = 1.5 and *h* = 0.199, respectively).
- *Conclusions:* These polymorphic markers will be used by grass breeders for uses including the improvement of commercial turfgrass cultivars, and by population geneticists to study different species of the *Epichloë* genus.

Key words: Ascomycota; Clavicipitaceae; endophyte; *Epichloë festucae*; *Festuca rubra*; fungus; grass.

Endophytic fungi are very common and important components in plant microbiomes. They are capable of infecting their host plant's tissues without causing obvious symptoms to the host (Hyde and Soyong, 2008). The *Epichloë* endophytes (Ascomycota: Clavicipitaceae) are one of the most studied systems of plant-endophyte associations because they form symbiotic relationships with several economically important turf and forage cool season grasses (Clay and Schardl, 2002). These endophytes are important agents influencing the growth and persistence of host grasses, and a genetically compatible endophyte infection has been demonstrated to provide a selective advantage to the host (Ahlholm et al., 2002; Saikkonen et al., 2006, 2010a, b). The *Epichloë* endophytes are a group of filamentous fungi that comprise sexual *Epichloë* species and their asexual derivatives, *Neotyphodium* species, which have been recently classified as *Epichloë* (Leuchtmann et al., 2014). *Epichloë festucae* Leuchtm., Schardl & Siegel is a fungal epichloid systemic endophyte, which systematically and intercellularly colonizes aboveground tissues and seeds of *Festuca rubra* L. by means of haploid hyphae. *Festuca rubra* is a perennial grass with rapid expansion worldwide in a wide range of ecosystems, and it is one of the most

important turfgrasses in temperate regions (Inda et al., 2008). Previously, nuclear microsatellite markers have been developed for *Epichloë* species by Moon et al. (1999) and expressed sequence tag (EST)-derived simple sequence repeats (SSRs) for pasture grass endophytes by van Zijll de Jong et al. (2003), and among those markers, four polymorphic nuclear microsatellite markers have been used in a population genetic study on *E. festucae* (Wäli et al., 2007). Because highly polymorphic genomic microsatellites are effective tools for studying population genetic characteristics, in this study, we aim to develop additional polymorphic microsatellite primers for *E. festucae*.

METHODS AND RESULTS

The unplaced genomic scaffold sequences of *E. festucae* were downloaded (GenBank accession no. JH158803–JH158837) and searched for ≥10 mono- and dinucleotide repeats, and for ≥8 tri-, tetra-, penta-, and hexanucleotide repeats by using MSATCOMMANDER (Faircloth, 2008). The selected marker regions possessed the maximum length of the repeat motif, a minimum distance of 100,000 bp between the repeat motifs within the same accession, and the presence of appropriate flanking sequences for primer design with the following criteria: primer length of 18–27 bp, GC content 40–60%, annealing temperature 55–58°C, and expected amplicon size of 100–300 bp. Twenty-four primer pairs were designed with Primer3 software (Rozen and Skaletsky, 2000). The forward primers were labeled with fluorescent dyes for automated electrophoresis, and the primers were obtained from Oligomer Oy (Helsinki, Finland).

To isolate *E. festucae* from endophyte-infected (E+) plants of *F. rubra*, three leaves were collected from each selected tiller from pots containing replanted *F. rubra* in the greenhouse of Ruissalo Botanical Garden, Finland. The plant material was kept at 4°C for 24 h, followed by surface sterilization, including a treatment in 75% ethanol for 30 s, 4% sodium hypochlorite for 3 min, and 75%

¹Manuscript received 26 September 2014; revision accepted 4 November 2014.

The research leading to these results has received funding from the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement no. 262693 (INTERACT).

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doi:10.3732/apps.1400093

TABLE 1. Characteristics of the 15 nuclear microsatellite markers developed for the endophyte fungus *Epichloë festucae*.^a

| Locus | Primer sequences (5'–3') | Repeat motif | Starting position (bp) | Allele size range (bp) ^b | GenBank accession no. |
|---------|--|--|------------------------|-------------------------------------|-----------------------|
| EF1SSR | F: 6FAM-ATCTGATTGAAACCCGGCG R: AGCTCTCTTTCTCCCCACAC | (A) ₃₆ (G) ₈ | 92,753 | 169–189 | AFRX01000154 |
| EF2SSR | F: 6FAM-GCGTTTTGGGACGGTTATGT R: GGTCACGTCATACTGAGTGC | (AT) ₁₂ (GT) ₂₁ | 45,291 | 144–168 | AFRX01000490_3 |
| EF4SSR | F: HEX-TGACTCAAGAAACGGTGCAG R: GCAGCGAACTTCCATGTGTA | (CT) ₂₀ | 97,543 | 198–226 | AFRX01000056_1 |
| EF5SSR | F: 6FAM-TCATACAGGATTAGTGGCCCC R: GTCAACTTTTTCATTCCCGTCCCT | (AC) ₁₇ | 54,068 | 217–351 | AFRX01000491 |
| EF6SSR | F: HEX-ACACTTGCTTTTGGAGCAT R: GCGCTCAACTTCGTCTCTCT | (AG) ₁₆ | 54,068 | 218–250 | AFRX01000295 |
| EF7SSR | F: 6FAM-GGCACAAGGACAGGACAT R: AGCAATTGTTCCGGGAATCAG | (TA) ₁₅ | 125,913 | 94–104 | AFRX01000004_4 |
| EF10SSR | F: 6FAM-ACTCTGACGGCTGACACTC R: AAGGGAAAAAGCGAAGAAGC | (GTT) ₈ (CCT) ₁₈ | 104,071 | 224–228 | AFRX01000322_2 |
| EF12SSR | F: HEX-TGCTCAACGATTCTTCGTG R: GGGCAAACATCAGTTCGATT | (CGA) ₁₃ | 2653 | 152 | AFRX01000322_2 |
| EF14SSR | F: 6FAM-ATTAGTGTGGCAGCCGATG R: TGGTGAACAACCCCGGAAT | (AGG) ₁₁ (GGT) ₇ | 19,493 | 212–234 | AFRX01000027_1 |
| EF15SSR | F: HEX-CACAGGTGCGCTTGTCAAC R: AACGGGAGTGAGACAGCATC | (CAT) ₈ TAT(CAT) ₆ | 21,195 | 215–237 | AFRX01000059_2 |
| EF19SSR | F: HEX-TGCAGGTCTCGTCTTCTCTC R: GGACGATGCAAATGACTGACA | (GCCT) ₁₃ | 14,731 | 198–319 | AFRX01000166 |
| EF20SSR | F: 6FAM-TTGAGTACAGACAGGACGG R: CGCTCAGATGTTGGATGACG | (AAGC) ₁₃ | 10,240 | 164–188 | AFRX01000153 |
| EF21SSR | F: HEX-GATTAGACACGACGCGGAAG R: CCCTGTCTGTTATGGACTCGT | (CATT) ₁₂ | 84,927 | 130–312 | AFRX01000271 |
| EF22SSR | F: HEX-GCAATCCCAAAACATGACGC R: GCAAAACATGTGAAACGGCC | (GAGT) ₁₂ | 49,308 | 103–258 | AFRX01000490_2 |
| EF24SSR | F: HEX-CCGAGTACTATGGTGGCAA R: CGACTTCCATGCACACTGTT | (ACTCTC) ₉ | 98,200 | 197–258 | AFRX01000156 |

^aAnnealing temperature = 57°C.

^bThe size ranges (bp) are based on 70 samples representing European populations located in Finland, the Faroe Islands, and Spain ($N = 8–10$ for each population); see Appendix 1 for population information.

ethanol for 15 s. Then, a leaf was cut into five segments and planted on autoclaved Petri dishes containing 5% potato dextrose agar (PDA). Agar plates were stored at room temperature until mycelium emerged from the plated leaf fragments, after which a small sample of mycelium was transferred to a new PDA plate on a piece of sterile cellophane (9 cm in diameter). *Epichloë festucae* identity was determined based on the morphological characteristics observed in cultures, and based on the sequences of the ITS1, 5.8S rRNA, and ITS2 region of a set of isolates from different locations, compared with GenBank resources (<http://www.ncbi.nlm.nih.gov>) using BLAST searches. PCR amplification of

the ITS1, 5.8S rRNA, and ITS2 region was performed using primers ITS1 and ITS5 (<http://www.fungalbarcoding.org/>). *Epichloë festucae* is the only systemic fungus described for *F. rubra*, and the systemic endophyte has always been *E. festucae* when we have previously sequenced fungi from *F. rubra* (e.g., Wäli et al., 2007). The risk that the mycelium growing on PDA corresponds to another related fungal endophyte different from *E. festucae* is marginal, especially as grasses are commonly assumed to be infected by only one systemic fungus. Replanted agar plates were stored at room temperature until the growth of the mycelium was sufficient for DNA extraction. Mycelium growth was

TABLE 2. Characteristics of 14 nuclear polymorphic microsatellite loci in eight populations of *Epichloë festucae*.^a

| Locus | FAS1 ($n = 8$) | | FAS2 ($n = 8$) | | FAS5 ($n = 8$) | | FAS6 ($n = 8$) | | RBS1 ($n = 8$) | | SPGD ($n = 10$) | | SPLV ($n = 10$) | | SPPOR ($n = 10$) | | All ($n = 70$) | |
|---------|---------------------|-------|---------------------|-------|---------------------|-------|---------------------|-------|---------------------|-------|----------------------|-------|----------------------|-------|-----------------------|-------|------------------|-------|
| | A | h | A | h | A | h | A | h | A | h | A | h | A | h | A | h | A | h |
| EF1SSR | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 3 | 0.607 | 2 | 0.533 | 2 | 0.533 | 2 | 0.200 | 6 | 0.700 |
| EF2SSR | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 2 | 0.250 | 1 | 0.000 | 3 | 0.733 | 3 | 0.600 | 2 | 0.467 | 6 | 0.727 |
| EF4SSR | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 2 | 0.556 | 4 | 0.778 | 1 | 0.000 | 7 | 0.706 |
| EF5SSR | 3 | 0.679 | 2 | 0.536 | 2 | 0.536 | 2 | 0.571 | 2 | 0.250 | 4 | 0.800 | 3 | 0.511 | 3 | 0.378 | 9 | 0.838 |
| EF6SSR | 2 | 0.250 | 1 | 0.000 | 2 | 0.250 | 1 | 0.000 | 1 | 0.000 | 6 | 0.889 | 3 | 0.622 | 3 | 0.511 | 12 | 0.749 |
| EF7SSR | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 3 | 0.600 | 2 | 0.200 | 2 | 0.556 | 4 | 0.598 |
| EF10SSR | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 2 | 0.467 | 3 | 0.644 | 3 | 0.511 | 5 | 0.702 |
| EF14SSR | 2 | 0.250 | 1 | 0.000 | 1 | 0.000 | 3 | 0.714 | 1 | 0.000 | 3 | 0.511 | 3 | 0.733 | 4 | 0.711 | 8 | 0.767 |
| EF15SSR | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 2 | 0.250 | 1 | 0.000 | 2 | 0.356 | 4 | 0.778 | 1 | 0.000 | 7 | 0.436 |
| EF19SSR | 2 | 0.536 | 2 | 0.571 | 2 | 0.536 | 3 | 0.679 | 1 | 0.000 | 4 | 0.711 | 5 | 0.800 | 4 | 0.733 | 14 | 0.874 |
| EF20SSR | 1 | 0.000 | 2 | 0.571 | 2 | 0.429 | 1 | 0.000 | 1 | 0.000 | 2 | 0.200 | 3 | 0.733 | 2 | 0.556 | 5 | 0.435 |
| EF21SSR | 2 | 0.536 | 2 | 0.429 | 2 | 0.536 | 2 | 0.536 | 3 | 0.607 | 7 | 0.911 | 6 | 0.778 | 5 | 0.844 | 16 | 0.868 |
| EF22SSR | 2 | 0.429 | 3 | 0.679 | 3 | 0.464 | 1 | 0.000 | 2 | 0.429 | 4 | 0.533 | 6 | 0.867 | 7 | 0.933 | 15 | 0.861 |
| EF24SSR | 2 | 0.250 | 2 | 0.571 | 1 | 0.000 | 1 | 0.000 | 1 | 0.000 | 4 | 0.778 | 3 | 0.600 | 3 | 0.644 | 9 | 0.779 |
| Mean | 1.6 | 0.209 | 1.5 | 0.240 | 1.5 | 0.196 | 1.6 | 0.214 | 1.4 | 0.135 | 3.4 | 0.613 | 3.6 | 0.656 | 3.0 | 0.503 | 8.8 | 0.717 |

Note: A = number of alleles per locus; h = unbiased haploid diversity; n = sample size.

^aGeographic coordinates for the populations are provided in Appendix 1.

scraped from the cellophane into an Eppendorf tube for DNA extraction. DNA was extracted from pure cultures of *E. festucae* with the E.Z.N.A. Plant DNA Kit (Omega Bio-Tek, Norcross, Georgia, USA), and a NanoDrop Lite spectrophotometer (Thermo Fisher Scientific, Wilmington, Delaware, USA) was used to reveal the yield and purity of DNA. The PCR reactions were performed with a single microsatellite primer pair in a 10- μ L reaction mixture containing 5–10 ng genomic DNA, 1 \times GoTaq Flexi Buffer, 1.0 mM MgCl₂ solution, 0.2 mM of each dNTP, 0.2 μ M of each primer, and 1.25 units GoTaq G2 HotStart Polymerase (Promega Corporation, Madison, Wisconsin, USA). PCR reactions were performed in a C1000 Thermal Cycler (Bio-Rad, Applied Biosystems, Foster City, California, USA) as follows: an initial denaturation at 95°C for 2 min; followed by 30 cycles at 95°C for 30 s, 57°C for 30 s, and 73°C for 30 s; and a final extension at 73°C for 5 min. Each PCR product was amplified singly. The amplification success was controlled with a set of PCR products using 2% agarose gels (SeaKem LE Agarose; Lonza, Rockland, Maine, USA). The products were run on an ABI 3130xl Genetic Analyzer using the GeneScan 500 ROX Size Standard (Applied Biosystems) at the Institute of Biotechnology, University of Helsinki, Finland, and assigned to allelic sizes with Peak Scanner version 1 software (Applied Biosystems). The unbiased haploid diversity (h) and the number of alleles (A) per locus and population were calculated using GenAlEx version 6.5 (Peakall and Smouse, 2006, 2012).

Initially, 24 individuals originating from populations in the Faroe Islands ($N = 8$), Finland ($N = 8$), and Spain ($N = 8$) were screened to reveal the competence of the 24 primer pairs. Nine primer pairs out of 24 were rejected from the further analysis because of unclear patterns with multiple bands and allelic dropouts, whereas 15 primer pairs amplified reliably and produced clearly interpretable single bands, and these were used in the further analyses (Table 1). Fifteen loci were screened for polymorphism using 70 individuals originating from four different populations in the Faroe Islands, one population from Finland, and three populations from Spain (Tables 1 and 2). One locus was monomorphic while 14 loci revealed polymorphism with altogether 123 alleles (Table 1). The number of alleles per locus varied from four to 16 at the species level and from one to seven at the population level (Table 2). The unbiased haploid diversity per locus varied from 0.435 to 0.874 at the species level, and from 0.000 to 0.933 at the population level (Table 2). The Spanish populations possessed a considerably higher number of alleles and haploid diversity (on average $A = 5.1$ and $h = 0.591$, respectively) compared to northern populations (on average $A = 1.5$ and $h = 0.199$, respectively).

CONCLUSIONS

Because endophytes have both scientific relevance and applied importance, these new polymorphic microsatellite markers will be useful for grass breeders, e.g., to improve commercial turfgrass cultivars of *F. rubra*, and for researchers to study different aspects of grass endophyte evolution. These markers presumably cross-amplify within the genus *Epichloë*, which includes host-specific endophytes of several important forage grasses (Leuchtmann et al., 2014).

LITERATURE CITED

- AHLHOLM, J. U., M. HELANDER, S. LEHTIMÄKI, P. WÄLI, AND K. SAIKKONEN. 2002. Vertically transmitted endophytes: Effects of environmental conditions. *Oikos* 99: 173–183.
- CLAY, K., AND K. SCHARDL. 2002. Evolutionary origins and ecological consequences of endophyte symbiosis with grasses. *American Naturalist* 160: S99–S127.
- FAIRCLOTH, B. C. 2008. MSATCOMMANDER: Detection of microsatellite repeat arrays and automated, locus-specific primer design. *Molecular Ecology Resources* 8: 92–94.
- HYDE, K. D., AND K. SOYTONG. 2008. The fungal endophyte dilemma. *Fungal Diversity* 33: 163–173.
- INDA, L. A., J. G. SEGARRA-MORAGUES, J. MULLER, P. M. PETERSON, AND P. CATALAN. 2008. Dated historical biogeography of the temperate Loliinae (Poaceae, Pooideae) grasses in the northern and southern hemispheres. *Molecular Phylogenetics and Evolution* 46: 932–957.
- LEUCHTMANN, A., C. W. BACON, C. L. SCHARDL, J. F. WHITE JR., AND M. TADYCH. 2014. Nomenclatural realignment of *Neotyphodium* species with genus *Epichloë*. *Mycologia* 106: 202–215.
- MOON, C. D., B. A. TAPPER, AND B. SCOTT. 1999. Identification of *Epichloë* endophytes in plants by microsatellite-based PCR fingerprinting assay with automated analysis. *Applied and Environmental Microbiology* 65: 1268–1279.
- PEAKALL, R., AND P. E. SMOUSE. 2006. GenAlEx 6: Genetic analysis in Excel. Population genetic software for teaching and research. *Molecular Ecology Notes* 6: 288–295.
- PEAKALL, R., AND P. E. SMOUSE. 2012. GenAlEx 6.5: Genetic analysis in Excel. Population genetic software for teaching and research—an update. *Bioinformatics (Oxford, England)* 28: 2537–2539.
- ROZEN, S., AND H. J. SKALETSKY. 2000. Primer3 on the WWW for general users and for biologist programmers. In S. Misener and S. A. Krawetz [eds.], *Methods in molecular biology*, vol. 132: Bioinformatics methods and protocols, 365–386. Humana Press, Totowa, New Jersey, USA.
- SAIKKONEN, K., P. LEHTONEN, M. HELANDER, J. KORICHEVA, AND S. H. FAETH. 2006. Model systems in ecology: Dissecting the endophyte-grass literature. *Trends in Plant Science* 11: 428–433.
- SAIKKONEN, K., S. SAARI, AND M. HELANDER. 2010a. Defensive mutualism between plants and endophytic fungi? *Fungal Diversity* 41: 101–113.
- SAIKKONEN, K., P. R. WÄLI, AND M. HELANDER. 2010b. Genetic compatibility determines endophyte-grass combinations. *PLoS ONE* 5: e11395.
- WÄLI, P., J. U. AHLHOLM, M. HELANDER, AND K. SAIKKONEN. 2007. Occurrence and genetic structure of the systemic grass endophyte *Epichloë festucae* in fine fescue populations. *Microbial Ecology* 53: 20–29.
- VAN ZIJLL DE JONG, E., K. M. GUTHRIDGE, G. C. SPANGENBERG, AND J. W. FOSTER. 2003. Development and characterization of EST-derived simple sequence repeat (SSR) markers for pasture grass endophytes. *Genome* 46: 277–290.

APPENDIX 1. Voucher information for *Epichloë festucae* isolates used in this study.

| Population code | Locality | Geographic coordinates | Altitude (m) | Habitat | Voucher specimen of host plant ^a |
|-----------------|-------------------------|-----------------------------|--------------|--------------------|---|
| FAS1 | Mykines, Faroe Islands | 62°5'50.7"N, 7°40'55.9"W | 125 | Meadow | H1762448 |
| FAS2 | Vidoy, Faroe Islands | 62°22'3.4"N, 6°32'31.8"W | 148 | Meadow | H1762445 |
| FAS5 | Vagar, Faroe Islands | 62°6'58.6"N, 7°26'42.5"W | 246 | Meadow | H1763054 |
| FAS6 | Eysturoy, Faroe Islands | 62°17'24.4"N, 7°2'9.7"W | 316 | Meadow | H1762447 |
| RBS1 | Kevo, Finland | 69°54'35.1"N, 27°2'0.15"E | 73 | Riverbank | H1762450 |
| SPGD | Cáceres, Spain | 40°12'1.12"N, 5°45'11.03"W | 768 | Xerophytic forest | H1762444 |
| SPLV | Salamanca, Spain | 40°56'20.16"N, 6°7'6.60"W | 863 | Grassland "dehasa" | H1762449 |
| SPPOR | Salamanca, Spain | 40°58'24.28"N, 5°57'33.69"W | 812 | Grassland "dehasa" | H1762446 |

^aVouchers deposited at the Botanical Museum (H), University of Helsinki.