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Paralog Re-Emergence: A Novel, Historically Contingent Mechanism in the Evolution of Antimicrobial Resistance

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Abstract

Evolution of resistance to drugs and pesticides poses a serious threat to human health and agricultural production. CYP51 encodes the target site of azole fungicides, widely used clinically and in agriculture. Azole resistance can evolve due to point mutations or overexpression of CYP51, and previous studies have shown that fungicide-resistant alleles have arisen by de novo mutation. Paralogs CYP51A and CYP51B are found in filamentous ascomycetes, but CYP51A has been lost from multiple lineages. Here, we show that in the barley pathogen Rhynchosporium commune, re-emergence of CYP51A constitutes a novel mechanism for the evolution of resistance to azoles. Pyrosequencing analysis of historical barley leaf samples from a unique long-term experiment from 1892 to 2008 indicates that the majority of the R. commune population lacked CYP51A until 1985, after which the frequency of CYP51A rapidly increased. Functional analysis demonstrates that CYP51A retains the same substrate as CYP51B, but with different transcriptional regulation. Phylogenetic analyses show that the origin of CYP51A far predates azole use, and newly sequenced Rhynchosporium genomes show CYP51A persisting in the R. commune lineage rather than being regained by horizontal gene transfer; therefore, CYP51A re-emergence provides an example of adaptation to novel compounds by selection from standing genetic variation.

Key words: standing variation, gene duplication, resistance, fungicides, triazoles, Rhynchosporium.

Introduction

Resistance to drugs and pesticides is a major challenge in medicine (McKenna 2013) and agriculture (Heckel 2012). Understanding the evolutionary mechanisms involved in the emergence and spread of resistance can aid resistance risk assessment and management (MacLean et al. 2010).

One relevant evolutionary question is the extent to which populations adapt to novel environments, such as a new biocide, through de novo mutations or through selection from standing genetic variation, as this will affect the probability and speed of emergence of resistant alleles (Hermisson and Pennings 2005). Previous studies have indicated de novo origins for fungicide resistance mutations (Torriani et al. 2009; Camps et al. 2012). Selection from standing variation can be inferred from the population genetic signature of selection, or by tracing the history of the selected allele (Barrett and Schluter 2008). In this study, we have taken the second approach, following the evolutionary history of CYP51A in Rhynchosporium commune through comparative genomics and analysis of historical infected plant samples.

Duplicate genes have long been considered an important source of genetic adaptive potential (Ohno 1970; Zhang 2003; Dittmar and Liberles 2010). Extensive research has considered the origin and fate of duplicated genes, but focusing on the likelihood of emergence of copy number variants (Lynch and Conery 2000); loss or change of function through pseudogenization, neofunctionalization, or subfunctionalization (Conant and Wolfe 2008; Innan and Kondrashov 2010); and mechanisms of functional divergence before or after duplication (Hughes 1994; Näsvall et al. 2012); around the time of duplication under given conditions of selection and drift, rather than future changes if selective pressures alter. In this study, the use of historical samples enables changes in duplicate gene frequency over time to be measured directly, revealing responses to changes in selection.

The azoles are widely used as both clinical and agricultural fungicides (Kelly et al. 1993). Clinically, the importance of antifungal therapies has increased as HIV, transplant antirejection drugs, and some cancer treatments leave patients immunocompromised and vulnerable to fungal infections (Denning and Hope 2010). In agriculture, crop diseases result in yield losses of 10–15% of global food production (Oerke and Dehne 2004; Strange and Scott 2005), a continual obstacle to feeding a growing population. In 2005, azoles represented 25.3% of the $8.9 billion global agricultural fungicide
market (Morton and Staub 2008). The target site of the azoles is fungal CYP51. CYP51 is a cytochrome P450, sterol 14α-demethylase, involved in the biosynthesis of ergosterol in fungi, cholesterol in mammals, and sitosterol in plants (Lepesheva and Waterman 2007).

Recently, some ascomycete fungi have been found to possess multiple CYP51 paralogs, with two paralogs, CYP51A and CYP51B, in Aspergillus fumigatus (Mellado et al. 2001), A. nidulans (Da Silva Ferreira et al. 2005), and Magnaporthe oryzae (Yan et al. 2011), and three in A. oryzae (Da Silva Ferreira et al. 2005) and Fusarium spp. (Deng et al. 2007). The reasons why some species possess multiple CYP51 paralogs, and others only one, are not yet known. Knocking out the CYP51A paralog from wild-type isolates of A. fumigatus (Mellado et al. 2005) and Fusarium graminearum (Fan et al. 2013) resulted in increased azole sensitivity, suggesting that the presence of additional CYP51 paralogs can confer reduced intrinsic azole sensitivity.

Acquired reductions in sensitivity to azoles may result from mutations or overexpression of CYP51. Various point mutations, with quantitative, interacting effects on azole sensitivity, have been reported in the single CYP51 paralog of the clinical pathogen Candida albicans (Morio et al. 2010) and the wheat pathogen Mycosphaerella graminicola (Cools et al. 2010). Reduced azole sensitivity due to constitutive overexpression of CYP51 was first reported in citrus green mould, Penicillium digitatum (Hamamoto et al. 2000). A combination of promoter changes resulting in overexpression and point mutations in the coding sequence has been reported in the CYP51A paralog in clinical isolates of A. fumigatus (Mellado et al. 2007). Nontarget-site mechanisms, such as enhanced efflux (de Waard and van Nistelrooy 1980) or altered sterol metabolism (Kelly et al. 1995), may also reduce azole sensitivity. Reduced sensitivity to azoles has now been reported in the field or in field isolates of over 20 plant pathogens (Fungicide Resistance Action Committee 2013, www.frac. info, last accessed April 16, 2014).

Rhynchosporium commune Zaffarano, McDonald, and Linde is an ascomycete fungal pathogen causing barley leaf blotch or scald. Previously known as R. secalis (Oud.) Davis (Caldwell 1937), it has recently been shown that R. secalis s.l. comprises three distinct host-specialized lineages, with R. secalis s.s. now referring only to the rye-infesting species, R. agropyri infecting Agropyron spp. and R. commune infecting barley (Zaffarano et al. 2011). Rhynchosporium commune causes necrotic lesions on infected leaves, resulting in grain yield reductions of up to 30% if untreated (Mayfield and Clare 1991). Although some barley varieties provide partial resistance, control is still heavily reliant on fungicides. In 2010, winter barley crops in the United Kingdom received an average of 2.1 fungicide applications, with 98.5% of crop area treated, and 54% of treatments containing an azole (Garthwaite et al. 2011).

The first azole to be used on barley in the United Kingdom was introduced in the mid-1970s. By 1985, surveys of azole sensitivity in R. commune revealed a 5- to 10-fold decrease in sensitivity to the earlier azoles relative to baseline testing in 1975–1981 (Kendall et al. 1993). Since the introduction of epoxiconazole in the late 1990s and prothioconazole in the mid-2000s, further sensitivity shifts have affected these compounds, but they retain some effectiveness in the field (Oxley et al. 2008). The mechanisms responsible for these azole sensitivity shifts in R. commune were not known.

The classical experiments at Rothamsted Research in Hertfordshire, UK, are field experiments studying the long-term effects of different agricultural practices and other factors affecting crop production and the environment. Broadbalk is the world’s oldest continually running agricultural experiment, growing winter wheat since 1843, and the Hoosfield spring barley experiment started 9 years later. Throughout the history of the experiment, plant and soil samples have been retained in the Rothamsted Archive. This enables the use of new analytical techniques on historical samples, such as quantitative polymerase chain reaction (qPCR) to quantify pathogen levels (Bearchell et al. 2005), or pyrosequencing to quantify alleles within populations (Gruber et al. 2002).

Rhynchosporium commune isolates were characterized for sensitivity to four azoles, and a sensitivity shift was confirmed. Two CYP51 genes were sequenced from R. commune and shown to be paralogs CYP51A and CYP51B (sensu Mellado et al. 2001), along with a pseudogene, CYP51A-p. The azole sensitivity shift was not correlated with point mutations or constitutive overexpression of either paralog, but CYP51A was present only in less sensitive isolates. CYP51A was upregulated in response to tebuconazole and complements yeast CYP51; therefore, CYP51A, where present, encodes an additional sterol 14α-demethylase with inducible overexpression. Phylogenetic analysis of fungal CYP51s indicates that CYP51A and CYP51B originate from a gene duplication event basal to the filamentous ascomycetes, followed by multiple losses of CYP51A. Pyrosequencing analysis of samples from the Hoosfield long-term spring barley experiment revealed that CYP51A had declined in the R. commune population by the start of the 20th century, but re-emerged in the mid-1980s under selection by azoles.

**Results**

**Ascomycete CYP51 Paralogs**

CYP51 paralogs from fungal genomes on the Broad Institute server, along with R. commune CYP51 genes and pseudogene, are shown in supplemental figure S1, Supplementary Material online, with gene names according to Nelson (2009). The maximum-likelihood phylogenetic tree is summarized in figure 1 and shown in full in supplemental figure S1, Supplementary Material online. Basidiomycetes and hemiascomycete yeasts each possess a single CYP51 paralog, apart from an independent duplication in Coprinopsis cinerea. CYP51 gene duplication took place around the origin of the filamentous ascomycetes, forming clades CYP51A, CYP51B, and CYP51C. All species studied have retained a CYP51B paralog, but CYP51A has been lost from multiple lineages, and CYP51C is found only in Fusarium spp. Further duplications of CYP51A and CYP51B have taken place in some Aspergillus species. The A. flavus “CYP51C” described by Liu et al.
(2012) appears from this phylogeny to be a second CYP51A. One R. commune CYP51 falls within the CYP51B clade, where its closest relatives are Botrytis cinerea and Sclerotinia sclerotiorum CYP51B. The other R. commune CYP51 falls within the CYP51A clade, where its closest relatives are sordariomycetes including M. oryzae as the sequenced leotiomycetes lack CYP51A. The R. commune CYP51 pseudogene is sister to R. commune CYP51A, and is therefore referred to as CYP51A-p.

**Triazole Sensitivity in R. commune**

Sensitivity of 57 R. commune isolates to the azole fungicides propiconazole, tebuconazole, epoxiconazole, and prothiocotonazole was measured by in vitro bioassay ( supplementary table S2, Supplementary Material online). Triazoles demonstrate partial cross-resistance, so a principal component analysis (PCA) was carried out (fig. 2). 75.4% of variance was encompassed by PC1, representing overall positive cross-resistance against the four triazoles, with all loadings positive. A further 17.2% of variance was encompassed by PC2, with positive loadings for propiconazole and tebuconazole but a negative loading for prothioconazole, showing incomplete cross-resistance between prothioconazole and the other azoles. The most sensitive group of isolates can be separated from the others by PC1 alone, indicating an initial sensitivity shift conferring positive cross-resistance against all four azoles tested. A further shift from intermediate to less-sensitive isolates, and further variation within the less-sensitive group, involves variation in PC2 as well, so this shift shows only partial cross-resistance, with prothioconazole affected differently from the other compounds.

Isolates from each sensitivity group were selected for molecular analysis. Sensitivity profiles for these isolates are shown in figure 3. CYP51A and CYP51B were sequenced for these isolates (GenBank accession numbers KF753641–KF753674). No single nucleotide polymorphisms (SNPs) correlated withazole sensitivity, but functional CYP51A sequences were obtained from the intermediate and less-sensitive isolates, whereas a pseudogene, with a frameshift indel and premature stop codons, was sequenced from the sensitive isolates.

A polymerase chain reaction–restriction fragment length polymorphism (PCR-RFLP) assay was developed to distinguish CYP51A from CYP51A-p. This revealed that sensitive isolates possess CYP51A-p but not CYP51A, whereas intermediate and less sensitive isolates possess both CYP51A and CYP51A-p ( supplementary fig. S2, Supplementary Material online). This difference in CYP51A copy number was confirmed by Southern blot ( supplementary fig. S2, Supplementary Material online). CYP51A-p was sequenced from additional isolates (GenBank accession numbers KF753666–KF753674) and all contained premature stop codons.

**Rhynchosporium commune CYP51A Expression**

To test whether R. commune CYP51A still functions as a sterol 14α-demethylase, R. commune CYP51A and CYP51B were expressed in a Saccharomyces cerevisiae strain in which the native CYP51 is under the control of a tetracycline-repressible
promoter. *Rhynchosporium commune* CYP51A and CYP51B were each able to complement *S. cerevisiae* CYP51 (fig. 4). Yeast transformants were then tested for triazole sensitivity. There was little difference in fungicide sensitivity, to triazoles or to the non-DMI cycloheximide, between the CYP51A and CYP51B transformants (fig. 4b).

Expression analysis of *R. commune* CYP51A and CYP51B was carried out. No differences in constitutive expression of either paralog were correlated with azole sensitivity. However, following the addition of tebuconazole, CYP51B was only upregulated around 5-10 fold if at all, whereas CYP51A, where present, was upregulated around 100-fold. Therefore, CYP51A expression is more inducible in response to the effects of azoles than CYP51B (fig. 5).

**Hoosfield Spring Barley Archive**

Amplification of a 52-bp fragment of a reference gene (*R. commune* β-tubulin) was successful from samples from 33 different years, from 1892 to 2012. The CYP51A nested PCR amplified products from *R. secalis* s.l. and not from *R. orthosporum*. All *R. secalis* s.l. DNA present in these samples was confirmed as *R. commune* with 5% detection limit, except 2012, which was excluded from further testing.

A pyrosequencing assay was developed to distinguish *R. commune* CYP51A from CYP51A-p (fig. 6). For most of the 20th century, the majority of the *R. commune* population at the Hoosfield experimental site lacked CYP51A, but in 1985, levels of CYP51A rapidly increased, and subsequently the majority of the *R. commune* population possesses CYP51A. Logit-transformed percentage data were analyzed with a Tukey multiple-comparison test. Levels of functional CYP51A in each year from 1985 onwards are significantly higher than in each year from 1892 to 1983. No year up to 1983 has significantly different levels of functional CYP51A from control isolates K1124 and FI12-63, which have only CYP51A-p, whereas no year from 1985 onwards has significantly different levels of CYP1A from isolates 788 and R9528.4, which have both CYP51A and CYP51A-p (supplementary table S4, Supplementary Material online). A further replicate DNA extraction from the homogenized plant material gave similar results (supplementary table S4, Supplementary Material online).

**CYP51A in Rhynchosporium Species**

The genomes of three *R. commune* isolates, and one isolate each of *R. agropyri*, *R. secalis* s.s., and *R. orthosporum*, sister species to the *R. secalis* s.l. complex, have been sequenced. The genomes were searched for CYP51 paralogs (GenBank accession numbers KF753675–KF753687). All contain a single CYP51B. Two *R. commune* isolates contain CYP51A-p only, and one isolate contains CYP51A and CYP51A-p.
**Rhynchosporium agropyri** and **R. secalis s.s.** contain a CYP51A pseudogene, but with different stop codons from **R. commune** CYP51A-p, whereas **R. orthosporum** contained only a functional CYP51A. Therefore, a functional CYP51A was present in the most recent common ancestor of **R. orthosporum** and **R. commune**, followed by duplication of CYP51A and pseudogenization of one copy in the **R. commune** lineage, and loss of the functional copy from some isolates (fig. 7).

### Discussion

A 10-fold shift in azole sensitivity in **R. commune** is correlated with the presence of the CYP51A paralog. All isolates possess CYP51B and a CYP51A-p pseudogene, but the functional CYP51A is absent from azole sensitive isolates and present in less-sensitive isolates. Further selection for reduced azole sensitivity among isolates with CYP51A has resulted in a further 10-fold difference in sensitivity to some azoles, which is not correlated with mutations or overexpression of either CYP51 paralog, implying that an additional, nontarget-site mechanism is responsible for this second shift.

Analysis of **R. commune** populations in barley samples from Hertfordshire, UK, shows an increase in CYP51A frequency in the population from 1985, with CYP51A present in the majority of the population thereafter. Similarly, the oldest studied isolates lack CYP51A, whereas most modern UK isolates have CYP51A. This correlates with a shift in triazole sensitivity reported in UK field populations between baseline monitoring from 1975 to 1981 and further surveys from 1985 onwards (Kendall et al. 1993). This demonstrates the value of the Rothamsted Classical Experiment archives to analyze past evolutionary changes involving mutations which have only now been identified.

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**FIG. 5.** Expression of (a) CYP51A and (b) CYP51B in **Rhynchosporium commune**, relative to isolate R 9528.4 constitutive expression, with β-tubulin as endogenous control. Light gray: constitutive expression, without fungicide; dark gray: induced expression, following the addition of 1 μg ml⁻¹ tebuconazole. Error bars indicate standard error of biological replicates. *CYP51A not present in these isolates: A low level of amplicon results from nonspecific amplification of CYP51A-p.

**FIG. 6.** Percentage of functional CYP51A in **Rhynchosporium commune** isolates, and populations sampled from the Hoosfield experiment at Rothamsted Research, UK. Isolate 1: K1124; 2: FI12-63; 3: 788; 4: R 9528.4. Isolates K1124 and FI12-63 contain CYP51A-p only; isolates 788 and R 9528.4 contain both CYP51A-p and functional CYP51A. Error bars indicate standard error of five technical replicates.

**FIG. 7.** Maximum-likelihood phylogeny of coding nucleotide sequences of CYP51 paralogs sequenced from **Rhynchosporium** species, with **Magnaporthe oryzae** CYP51A, **Botrytis cinerea** CYP51B, and **Fusarium graminearum** CYP51C. Rooted with **Candida albicans** CYP51 outgroup. Node labels indicate bootstrap support.

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The mechanism by which CYP51A reducesazole sensitivity appears to be inducible target-site overexpression. *Rhynchosporium commune* CYP51A is able to complement *S. cerevisiae* CYP51, so it is a functional sterol 14α-demethylase, and in *R. commune*, CYP51A is upregulated following exposure to an azole, so CYP51A may be able to maintain CYP51 function when CYP51B is inhibited by azoles. Previously reported cases of reduced azole sensitivity due to target-site overexpression have all involved constitutive overexpression of an existing paralog due to promoter insertions or gene duplication. Acquired reductions in azole sensitivity due to CYP51 duplication have been reported due to chromosome duplication in *C. glabrata* (Marichal et al. 1997); isochromosome formation, with duplication of chromosome arm 5L containing CYP51, two efflux pump encoding genes and one ABC transporter transcription factor, in *C. albicans* (Selmecki et al. 2006); and disomy of chromosome 1, containing one ABC transporter transcription factor, in *C. albicans* and *C. neoformans*. 

Intrinsic azole sensitivity in *S. cerevisiae* CYP51, maintains the original pattern (Gu et al. 2005). Intrinsic sequence expression evolves primarily in one copy whereas the other changes in substrate (Skamnioti et al. 2008), and often altered transcriptional regulation rather than transcriptional regulation, including greater upregulation in response to azoles. Neofunctionalization of fungal genes often involves changes in transcriptional regulation rather than changes in substrate (Skamnioti et al. 2008), and often altered expression evolves primarily in one copy whereas the other retains the original pattern (Gu et al. 2005). Intrinsic sequence differences between CYP51A and CYP51B contribute to reduced intrinsicazole sensitivity in *A. fumigatus* (Martel et al. 2010) and *F. graminearum* (Fan et al. 2013), but *R. commune* CYP51A conferred similarazole sensitivity to CYP51B when expressed in yeast, suggesting that upregulation of CYP51A, rather than reducedazole binding due to intrinsic sequence differences, is the main mechanism of reducedazole sensitivity in *R. commune* isolates possessing CYP51A.

Although CYP51 paralogs have been extensively studied in a few species, such as *A. fumigatus* where CYP51A mutations conferazole resistance, in others species, knowledge of CYP51 paralog presence is based only on a single isolate selected for genome sequencing. Therefore, genome resequencing of multiple isolates may reveal paralog presence polymorphisms in other species, and possible multiple CYP51 paralogs should be considered in future when investigatingazole sensitivity shifts. Further investigation is also needed concerning the reasons for the emergence of CYP51A, and its retention in some fungal lineages, in the absence of selection by azoles. CYP51A expression is induced in CYP51B deletion mutants (Fan et al. 2013), as well as following CYP51 inhibition by azoles, suggesting that CYP51A is upregulated in response to disruption of ergosterol biosynthesis. Therefore, presence of this inducible CYP51, in addition to the constitutively expressed CYP51B found in all filamentous ascomycetes, would allow a fungus to respond to fluctuating ergosterol requirements, but it is not yet clear which aspects of fungal biology and lifestyle make this necessary in some species and not others.

Phylogenetic analysis places *R. commune* CYP51A in a monophyletic clade with other filamentous ascomycete CYP51As, which diverged from CYP51B around the origin of the filamentous ascomycetes, 320–520 Ma (Lücking et al. 2009). This indicates a single origin of CYP51A followed by multiple losses, rather than an independent recent origin in *R. commune*. However, the origin of CYP51A-p, and partial loss of CYP51A, in the *R. commune* lineage took place far more recently. *Rhynchosporium orthosporum* possesses a functional CYP51A and not a pseudogene, whereas the sequenced isolates of *R. agropyri* and *R. secalis* s.s. possess only a pseudogene. The *R. orthosporum* CYP51A forms a sister group to *R. commune* CYP51A and CYP51A-p. Therefore, CYP51A duplication took place in the *R. commune* lineage after it diverged from *R. orthosporum*, 14.5–35 ka BP (Zaffarano et al. 2008), but before the divergence of *R. agropyri* and *R. secalis* s.s., and *R. commune* from their most recent common ancestor, 1.3–3.6 ka BP (Zaffarano et al. 2008). This was followed in the *R. commune* lineage by pseudogenization of one copy, and loss of the functional copy in some of the population. Further study of *R. agropyri* and *R. secalis* s.s. would be needed to ascertain whether CYP51A pseudogenization occurred independently in these lineages or once in the *R. secalis* s.l. common ancestor, and whether any isolates of these species possess a functional CYP51A. The gene phylogeny confirms that CYP51A was retained within the *R. commune* lineage, and not regained by horizontal gene transfer, in contrast to the acquisition of antibiotic resistance genes in clinical bacteria by horizontal gene transfer from soil bacteria previously exposed to naturally occurring microbial antibiotics (Forsberg et al. 2012).

Having declined in the *R. commune* population, CYP51A later re-emerged under selection by azoles in the late 20th century. Most research into the origin and fate of duplicate genes considers possible outcomes in terms of loss or fixation in a species, and it has been demonstrated that most intraspecific gene copy number variations result from very recent duplication events, as older duplicates have already been lost or fixed, and most established, diverged duplicates are maintained by purifying selection (Schröder and Hahn 2010). Comparative genomics has revealed cases of fixed paralog losses following a change in selection in some taxa, such as repeated gene losses from the olfactory receptor gene family in microsmic mammals (Rouquier et al. 2000), or extensive gene losses in obligate parasites (Spanu et al. 2010). However, the Rothamsted archive samples, covering a time frame including a known change in selection, provide the temporal resolution to detect changes in paralog frequency over time, enabling us to detect the previous near-loss of a paralog followed by its re-emergence due to a further change in selection.

Furthermore, as phylogenetic analyses have shown that the functional CYP51A in *R. commune* originated long beforeazole use, its re-emergence provides an example of an adaptation to a new environment that has been selected from standing genetic variation rather than arising from a de novo mutation (Barrett and Schluter 2008), whereas previous studies of other fungicide resistance alleles have pointed to de novo mutational origins (Torriani et al. 2009; Camps et al.
2012). Although ancient origins have previously been demonstrated for resistance genes to antibiotics based on natural microbial products (D’Costa et al. 2011), the triazoles are synthetic in origin with no known natural analogs and therefore their use imposes a previously unencountered selective pressure. Standing variation may allow resistance to evolve more quickly, or may result in increased probability of fixation where the fitness benefit is smaller and a de novo mutation may have been lost through genetic drift (Hermisson and Pennings 2005). Furthermore, as this standing variation comprises a trait that has been lost from multiple ascomycete lineages, the availability of CYP51A re-emergence as an adaptive pathway is historically contingent upon CYP51A still having been present at low levels in the population at the point when selection pressures altered due to anthropogenic fungicide use.

**Materials and Methods**

Bioinformatic and Phylogenetic Analysis

CYP51 sequences were obtained from fungal genomes on the Broad Institute server (http://www.broadinstitute.org/science/data, last accessed April 16, 2014), along with *Mycobacterium* tuberculosis, *Trypanosoma cruzi*, *Homo sapiens*, *Arabidopsis thaliana* CYP51G1, and *Mus musculus* CYP51, with *Mus musculus* CYP7AT as an outgroup (Aoyama et al. 1996). A text search was carried out for annotated CYP51 genes, followed by BLAST searches against each genome with *S. cerevisiae* CYP51, and with CYP51A and CYP51C from the nearest available relative for species where these paralogs were not found. Start sites, introns, and stop sites were checked manually, and introns removed as they were too variable to align unambiguously. Predicted amino acid sequences were aligned using M-Coffee (Notredame et al. 2000), and the corresponding coding nucleotide alignment generated using PAL2NAL (Suyama et al. 2006). Model selection was carried out in jModelTest 0.1.1 (Posada 2008), selecting by AICc. Maximum-likelihood phylogenetic analysis was carried out in PhyML (Guindon and Gascuel 2003), implemented through the TOPALi v2.5 platform (Milne et al. 2009), using a TVM + I + G model, with 100 bootstrap runs.

**Fungicide Sensitivity Testing**

Isolates used are listed in [supplementary table S1](http://mbe.oxfordjournals.org/), [Supplementary Material](http://mbe.oxfordjournals.org/). Isolates had been stored as spore suspensions on silica gel at −80°C. Isolates were grown on Czapek dox agar with 0.5% mycological peptone, with an inoculum density of 1.25 × 10³ spores per 90 mm Petri dish, at 18°C for 10 days. Sensitivity testing was carried out as described by Pijls et al. (1994), using Sabouraud medium, *R. commune* spores at 1.25 × 10³ spores ml⁻¹, and the following technical-grade fungicides: epoxiconazole, 50 μg ml⁻¹ with 2.5-fold dilutions; prothioconazole, propiconazole, tebuconazole, 100 μg ml⁻¹ with 3-fold dilutions, repeated with 300 μg ml⁻¹ for less sensitive isolates. Plates were incubated at 18°C for 7 days, then fungal growth was measured by optical absorbance at 620 nm using an Optima Fluostar plate reader (BMG Labtech, Germany), in well-scanning mode with a 4 × 4 matrix of scanning points within a 3-mm diameter. The accompanying software was used to fit a dose–response curve (4-parameter fit) and calculate EC₅₀ values. Cross-resistance was assessed by PCA using the correlation matrix of log₁₀ transformed EC₅₀s for the four fungicides, in GenStat 14 th Edition (VSN International, Hertfordshire, UK).

**CYP51 Sequencing**

Initial fragments were amplified using degenerate primers CYP51 3F and CYP51A CIGEK rv for CYP51A, and DMIRES F1 and 14DM R2 for CYP1B ([supplementary table S3](http://mbe.oxfordjournals.org/), [Supplementary Material](http://mbe.oxfordjournals.org/)). The remainder of each gene (GenBank accession numbers KF753639–KF753640) was found by genome-walking using the GenomeWalker Universal Kit (Clontech, CA). Libraries were prepared from isolate 1130 (Rohel et al. 1998) genomic DNA, with restriction enzymes DraI, PvuII, EcoRV, and StuI. Three reactions in the 5’-direction and one in the 3’-direction were needed to obtain the complete coding sequence of CYP51A, and two reactions in the 5’-direction and one in the 3’-direction for CYP1B. Genome-specific primers (GSP1 and GSP2) used in successive reactions are listed in [supplementary table S3](http://mbe.oxfordjournals.org/), [Supplementary Material](http://mbe.oxfordjournals.org/). PCR products were purified using the Wizard SV Gel and PCR Clean-Up System, ligated with 2.5-fold dilutions; prothioconazole, propiconazole, tebuconazole, 100 μg ml⁻¹ with 3-fold dilutions, repeated with 300 μg ml⁻¹ for less sensitive isolates. Plates were incubated at 18°C for 7 days, then fungal growth was measured by optical absorbance at 620 nm using an Optima Fluostar plate reader (BMG Labtech, Germany), in well-scanning mode with a 4 × 4 matrix of scanning points within a 3-mm diameter. The accompanying software was used to fit a dose–response curve (4-parameter fit) and calculate EC₅₀ values. Cross-resistance was assessed by PCA using the correlation matrix of log₁₀ transformed EC₅₀s for the four fungicides, in GenStat 14 th Edition (VSN International, Hertfordshire, UK).

**PCR–RFLP Assay**

Two PCR reactions were carried out per isolate, one to amplify CYP51A and one to amplify CYP51A-p, using Phusion...
The probe was amplified from pGEM-T Easy plasmids containing exon 3.

Supplementary Material online) to amplify a 734-bp fragment of genomic DNA from isolates 788, K1124, and FI12-63 was described by Motteram et al. (2009). Ten micrograms of Southern F and Reverse 1D (supplementary table S3, Supplementary Material online) to amplify a 734-bp fragment of exon 3.

**Yeast Complementation**

*Rhynchosporium commune* CYP51A and CYP51B were amplified from a 1/10 dilution of isolate 788 cDNA using Easy-A High-Fidelity PCR Cloning Enzyme (Stratagene), with primers CYP51A pYES F2 and pYES R and CYP51B pYES F and pYES R (supplementary table S3, Supplementary Material online). PCR product was purified using the Wizard SV Gel and PCR Clean-Up System (Promega), and a sample of the CYP51A product digested with *PstI* and *HindIII* to confirm it was CYP51A and not CYP51A-p. *KpnI* and a *SacI* restriction sites were incorporated by the forward and reverse primers, respectively. An internal *KpnI* site was removed from CYP51B using the QuikChange II Site-Directed Mutagenesis Kit (Agilent Technologies, CA, USA) with primer pYES mut (supplementary table S3, Supplementary Material online). Cloning in yeast expression vector pYES2/CT (Invitrogen), transformation into *S. cerevisiae* YUG37/erg11 strain, and complementation analysis were carried out as described by Cools et al. (2010), with pYES-Mg51wt as a positive control. Fungicide sensitivity testing was carried out as in Cools et al. (2010), but with maximum fungicide concentrations of 0.005 μg ml⁻¹ for epoxiconazole and propiconazole, 0.05 μg ml⁻¹ for prothioconazole and tebuconazole and 5 μg ml⁻¹ for cycloheximide, all with 2-fold serial dilutions.

**CYP51 Expression**

*Rhynchosporium commune* isolates QUB 30-10, 788, K1124, QUB 12-3, FI12-63, R 9528.4, GKII 18-2-3, and RS 783 783 were grown liquid culture, in 100-ml Sabouraud liquid medium at 8°C, 150 rpm, with two biological replicates of treatment and control culture for each isolate. After 7 days, tebuconazole solution in acetone to a final concentration of 1 μg ml⁻¹ was added. An equal volume of acetone without tebuconazole was added to the control cultures. After 10 days, cultures were harvested by vacuum-filtration, then freeze-dried. RNA extraction was carried out with TRIzol Reagent (Invitrogen), according to manufacturer’s instructions, followed by overnight precipitation with 4 M lithium chloride and treatment with the TURBO DNA-free Kit (Applied Biosystems, CA). cDNA was synthesized with the Superscript III first-strand synthesis system (Invitrogen). End-point PCR reactions were carried out using Red Hot Taq (ABgene, Epsom, UK) with intron-spanning primer pair CYP51B Expression F and CYP51B Expression R (supplementary table S3, Supplementary Material online) to check for genomic DNA contamination.

Quantitative PCR was carried out using SYBR Green JumpStart Taq ReadyMix (Sigma), with CYP51B, CYP51A, and *β-tubulin* primers Expression F and Expression R (supplementary table S3, Supplementary Material online). Relative quantification was calculated by the 2^-ΔΔCt method (Livak and Schmittgen 2001), with *β-tubulin* as endogenous control and isolate R9528.4 without fungicide as calibrator sample.

**Hoosfield Long-Term Experiment and Pyrosequencing Assay**

Spring barley has been grown on the Hoosfield plot at Rothamsted Research, in Harpenden, UK, every year since 1852, apart from 1912, 1933, 1943, and 1967 when it was left fallow to control weeds. Dried leaf, grain, and soil samples have been retained each year. Straw samples used were from Plot 4A, receiving 48 kg N ha⁻¹ in the form of ammonium sulfate. From 1968, this plot was divided into four subplots receiving different nitrogen doses in the form of calcium ammonium nitrate, and samples used were from the subplot receiving 48 kg N ha⁻¹.

One gram of material was taken from the archive sample, ground using a sterilized pestle and mortar, then extraction buffer was added and DNA extractions carried out as described by Motteram et al. (2009), with two replicate extractions from each homogenized sample. *Rhynchosporium secalis* s.l. DNA presence and quality were tested by endpoint PCR amplification of a 520-bp fragment of reference gene *β-tubulin* using primers Rs F3 and Rs R3 (supplementary table S3, Supplementary Material online), and up to 3 years per decade were selected for analysis. *Rhynchosporium secalis* s.l. species present were identified based on a C/T SNP at nucleotide 391 of *β-tubulin* (Zaffarano et al. 2011), with a nested PCR using primers RhyUF1 and RhyUR1 then PyroRhF1Bio and PyroRHR1, followed by a pyrosequencing assay using the PyroMark system (Qiagen) and the PSQ96 instrument (Biotage, Uppsala, Sweden), programmed to analyze the sequence TC/TGCAGATCCAAAGGTAGAATTACA CT, using the nucleotide dispensation order ATCTGCGAGA, with primer PyroRhS1 (supplementary table S3, Supplementary Material online).

To distinguish CYP51A from CYP51A-p, a pyrosequencing assay was developed to detect a 4-bp indel at nucleotide 418. A nested PCR was carried out with primers Pyro F3 and Pyro R2 then primers Del F1 and Del R1 (supplementary table S3, Supplementary Material online) and the products pyrosequenced using the PyroMark system (Qiagen) and the PSQ96 instrument (Biotage), to analyze the sequence CA[TTTC]CTTCCAGCCCCAAAGATACAGCTCAT, using the nucleotide dispensation order GCATCGTCA, with primer Del S1 (supplementary table S3, Supplementary Material online).

**Rhynchosporium Spp. Genome Analysis**

The genomes of *R. commune* isolates UK7, AU2 (Lehnackers and Knoke 1990), and 13-13 (A. Avrova, The James Hutton Institute, UK) were sequenced at the BBSRC Genomics and Bioinformatics Facility and BBSRC Genomics and Bioinformatics Facility at Rothamsted, using Roche 454 sequencing technology. The genome assemblies were checked using CAP3 (Huang and Madan 1999), with CYP51A gene identified using the HMMER package (Eddy 1998).

**Plot 4A, receiving 48 kg N ha⁻¹** was added. An equal volume of ace-
Caldwell R. 1937. A BLAST search was carried out against substitution models were predicted with jModeltest, and coding nucleotides were aligned with PAL2NAL. CYP51 as an outgroup were aligned with M-Coffee, and GTR+ and Supplementary Material online, to confirm the genome as sequenced by Sanger sequencing, as described for CYP51 sequences translated. Each molecular biology and evolution, mbe.oxfordjournals.org/.

Supplementary Material online, to confirm the genome assembly. Predicted amino acid sequences, along with B. cinerea CYP51B and M. oryzae CYP51A (the closest relatives of C. commune in Supplementary fig S1, Supplementary Material online), F. graminearum CYP51C, and C. albicans CYP51 as an outgroup were aligned with M-Coffee, and phylogenetic reconstruction carried out in PhyML with the GTR+G model and 100 bootstrap runs.

Supplementary Material online, to confirm the genome assembly. Predicted amino acid sequences, along with B. cinerea CYP51B and M. oryzae CYP51A (the closest relatives of C. commune in Supplementary fig S1, Supplementary Material online), F. graminearum CYP51C, and C. albicans CYP51 as an outgroup were aligned with M-Coffee, and phylogenetic reconstruction carried out in PhyML with the GTR+G model and 100 bootstrap runs.

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References


Deng JX, Carbone I, Dean RA. 2007. The evolutionary history of cytochrome P450 genes in four filamentous Ascomycetes. BMC Evol Biol. 7:22.