

Extensive sampling of basidiomycete genomes demonstrates inadequacy of the white-rot/brown-rot paradigm for wood decay fungi

Robert Riley^a, Asaf A. Salamov^a, Daren W. Brown^b, Laszlo G. Nagy^c, Dimitrios Floudas^c, Benjamin W. Held^d, Anthony Levasseur^e, Vincent Lombard^f, Emmanuelle Morin^g, Robert Otillar^a, Erika A. Lindquist^a, Hui Sun^a, Kurt M. LaButti^a, Jeremy Schmutz^{a,h}, Dina Jabbourⁱ, Hong Luoⁱ, Scott E. Baker^j, Antonio G. Pisabarro^k, Jonathan D. Waltonⁱ, Robert A. Blanchette^d, Bernard Henrissat^f, Francis Martin^g, Dan Cullen^l, David S. Hibbett^{c,1}, and Igor V. Grigoriev^{a,1}

^aUS Department of Energy (DOE) Joint Genome Institute, Walnut Creek, CA 94598; ^bUS Department of Agriculture (USDA), Peoria, IL 61604; ^cDepartment of Biology, Clark University, Worcester, MA 01610; ^dUniversity of Minnesota, St. Paul, MN 55108; ^eInstitut National de la Recherche Agronomique, Unité Mixte de Recherche 1163, Aix-Marseille Université, 13288 Marseille, France; ^fCentre National de la Recherche Scientifique, Unité Mixte de Recherche 7257, Aix-Marseille Université, 13288 Marseille, France; ^gInstitut National de la Recherche Agronomique, Unité Mixte de Recherche 1136, Institut National de la Recherche Agronomique-Université de Lorraine, Interactions Arbres/Micro-organismes, 54280 Champenoux, France; ^hHudsonAlpha Institute of Biotechnology, Huntsville, AL 35806; ⁱDOE Great Lakes Bioenergy Research Center, Michigan State University, East Lansing, MI 48824; ^jEnvironmental Molecular Sciences Laboratory, Pacific Northwest National Laboratory, Richland, WA 99354; ^kDepartamento de Producción Agraria, Universidad Pública de Navarra, 31006 Pamplona, Spain; and ^lUSDA Forest Products Laboratory, Madison, WI 53726

Edited* by Thomas N. Taylor, University of Kansas, Lawrence, KS, and approved May 16, 2014 (received for review January 12, 2014)

Basidiomycota (basidiomycetes) make up 32% of the described fungi and include most wood-decaying species, as well as pathogens and mutualistic symbionts. Wood-decaying basidiomycetes have typically been classified as either white rot or brown rot, based on the ability (in white rot only) to degrade lignin along with cellulose and hemicellulose. Prior genomic comparisons suggested that the two decay modes can be distinguished based on the presence or absence of ligninolytic class II peroxidases (PODs), as well as the abundance of enzymes acting directly on crystalline cellulose (reduced in brown rot). To assess the generality of the white-rot/brown-rot classification paradigm, we compared the genomes of 33 basidiomycetes, including four newly sequenced wood decayers, and performed phylogenetically informed principal-components analysis (PCA) of a broad range of gene families encoding plant biomass-degrading enzymes. The newly sequenced *Botryobasidium botryosum* and *Jaapia argillacea* genomes lack PODs but possess diverse enzymes acting on crystalline cellulose, and they group close to the model white-rot species *Phanerochaete chrysosporium* in the PCA. Furthermore, laboratory assays showed that both *B. botryosum* and *J. argillacea* can degrade all polymeric components of woody plant cell walls, a characteristic of white rot. We also found expansions in reducing polyketide synthase genes specific to the brown-rot fungi. Our results suggest a continuum rather than a dichotomy between the white-rot and brown-rot modes of wood decay. A more nuanced categorization of rot types is needed, based on an improved understanding of the genomics and biochemistry of wood decay.

lignocellulose | phylogenomics | bioenergy

Fungi of the phylum Basidiomycota (basidiomycetes) comprise 32% of the described fungi (1) and are important to forestry (2–4), agriculture (5–7), and medicine (8–11). This diverse phylum includes the mushrooms (12–14); pathogens of plants (2), animals (9–11), and other fungi (15); osmotically tolerant molds (16); ectomycorrhizal symbionts like *Laccaria bicolor*, which are critical for plant growth; plant pathogens, such as rusts and smuts (7); and saprotrophs, including wood-decaying fungi (17).

The 26,000 basidiomycete taxa in the National Center for Biotechnology Information (NCBI) database (18, 19) are divided into three subphyla: Agaricomycotina (~22,000 taxa), Pucciniomycotina (~2,300 taxa), and Ustilaginomycotina (~1,000 taxa). Agaricomycotina includes many decomposers of wood and leaf litter (12, 17, 20–23) that produce lignocellulolytic enzymes that

have potential to be used in bioenergy production (24–27). Thus, much of sequencing effort at the US Department of Energy (DOE) Joint Genome Institute (JGI) (<http://jgi.doe.gov/fungi>) has targeted Agaricomycotina, particularly the Agaricomycetes (mushroom-forming fungi), with the large orders Agaricales (predominantly gilled mushrooms), Polyporales (wood-decaying polypores and others), and Boletales (porcini mushrooms and others) being especially deeply sampled.

A keen focus in the comparative genomics of Basidiomycota has concerned lineages of wood decay fungi (13, 17, 20–23, 28). For decades, two broad categories have been recognized: white rot and brown rot (29–31). During brown rot, cellulose is rapidly

Significance

Wood decay fungi have historically been characterized as either white rot, which degrade all components of plant cell walls, including lignin, or brown rot, which leave lignin largely intact. Genomic analyses have shown that white-rot species possess multiple lignin-degrading peroxidases (PODs) and expanded suites of enzymes attacking crystalline cellulose. To test the adequacy of the white/brown-rot categories, we analyzed 33 fungal genomes. Some species lack PODs, and thus resemble brown-rot fungi, but possess the cellulose-degrading apparatus typical of white-rot fungi. Moreover, they appear to degrade lignin, based on decay analyses on wood wafers. Our results indicate that the prevailing paradigm of white rot vs. brown rot does not capture the diversity of fungal wood decay mechanisms.

Author contributions: R.R., S.E.B., A.G.P., J.D.W., R.A.B., B.H., F.M., D.C., D.S.H., and I.V.G. designed research; R.R., D.W.B., L.G.N., D.F., B.W.H., A.L., E.M., and R.A.B. performed research; A.G.P., J.D.W., B.H., and D.S.H. contributed new reagents/analytic tools; R.R., A.A.S., D.W.B., L.G.N., D.F., A.L., V.L., E.M., R.O., E.A.L., H.S., K.M.L., J.S., D.J., and H.L. analyzed data; and R.R., D.W.B., J.D.W., R.A.B., B.H., D.C., D.S.H., and I.V.G. wrote the paper.

The authors declare no conflict of interest.

*This Direct Submission article had a prearranged editor.

Freely available online through the PNAS open access option.

Data deposition: The sequences reported in this paper have been deposited in the GenBank database [AYEP00000000 (*Botryobasidium botryosum*), AYUM00000000 (*Galerina marginata*), AYUL00000000 (*Jaapia argillacea*), and AYUK00000000 (*Pleurotus ostreatus*)].

¹To whom correspondence may be addressed. E-mail: IVGrigoriev@lbl.gov or dhibbett@clarku.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1400592111/-DCSupplemental.

depolymerized via oxidative mechanisms, whereas modified lignin remains as a polymeric residue (32–35). In contrast, white-rot fungi use hydrolases that gradually degrade cellulose while lignin is completely mineralized. Lignin degradation involves high-oxidation potential class II peroxidases (PODs) that, on the basis of conserved catalytic and Mn-binding sites, are classified as lignin peroxidase (LiP), manganese peroxidase (MnP), or versatile peroxidase (VP) (36–38). The first genomes of the white-rot fungus *Phanerochaete chrysosporium* and brown-rot fungus *Postia placenta* revealed a gene complement consistent with their respective modes of wood decay (22, 23). Further comparative genomics studies of larger sets of wood decay fungi supported a consistent relationship between decay patterns and several enzyme families. Specifically, white-rot fungi had high-oxidation potential PODs for lignin degradation as well as cellobiohydrolases for degrading crystalline cellulose. Classified in glycoside hydrolase (GH) families (39) GH6 and GH7, cellobiohydrolases attack cellulose in a synergistic manner and often carry a cellulose binding module (CBM1). In contrast, the genomes of brown-rot fungi did not encode PODs and the predicted cellobiohydrolase-encoding genes were generally absent or lacking a CBM1 domain.

Here, we present comparative analyses of 33 sequenced basidiomycete genomes (Table S1). Included are 22 wood decayers, of which *Galerina marginata*, *Pleurotus ostreatus*, *Botryobasidium botryosum*, and *Jaapia argillacea* are newly sequenced. The results call into question the prevailing white-rot/brown-rot dichotomy.

Results and Discussion

Phylogeny and Protein Conservation. A maximum-likelihood (ML) phylogeny (40) was inferred from protein sequence alignments of 183 conserved gene families (Fig. S14). Overall, the tree topology is consistent with prior studies using genome-scale datasets (17) as well as phylogenetic analyses using small numbers of genes (41), such as the sister group relationship between Ustilaginomycotina and Agaricomycotina, and the placement of *Wallemia sebi* (Wallemiomycetes) as the sister group of the rest of the Agaricomycotina (16). Brown-rot fungi are polyphyletic, as shown previously (17), and include species in Polyporales, Boletales, Gloeophyllales, and Dacrymycetales. Some aspects of the phylogeny remain uncertain: our placement of *Jaapia argillacea* as the sister group of the Gloeophyllales conflicts with a previous study using six genes (42); and *Auricularia delicata* was inferred as the sister group of *Piriformospora indica*, differing from multigene phylogenies (41, 43–45), which suggested that these lineages form a paraphyletic assemblage.

Gene families in 33 basidiomycetes and 30 other fungi (Table S2) with sequenced genomes were inferred by Markov chain (MCL) clustering (46) of all-vs.-all protein BLAST (47) alignments. Analysis of protein conservation suggests a conserved core fungal genome of ~5,000 genes (Fig. S1C). Roughly one-half of the proteins (49%) in Basidiomycota lack homologs in other groups of fungi, and 23% of Basidiomycota proteins are unique to a single organism (i.e., each of the 33 basidiomycetes analyzed harbored proteins not found in any other sampled species, ranging from 4% to 51%). In contrast, in Ascomycota, 30% of the proteins are phylum specific and 13% are organism specific (using a comparative set of 27 Ascomycota fungi; Table S2). We were able to assign functions from the Eukaryotic Clusters of Orthologs (KOG) (48) to 38% of Basidiomycota proteins (compared with 43% in Ascomycota); 74% of core proteins in both Basidiomycota and Ascomycota; and 17% of Basidiomycota-specific proteins (23% in Ascomycota) (Fig. S2).

Diversity of CAZymes and Associated Activities in Basidiomycota. Thirty-three basidiomycete genomes were searched for genes whose protein products are implicated in the breakdown of the polysaccharide portion of plant cell walls (cellulose, hemicellulose, pectin) using the CAZy database pipeline (39, 49). The

number of genes in each CAZy family, in each organism, is presented in Dataset S1.

Cellulolytic families. During white-rot decay, cellulose is targeted primarily by hydrolytic enzymes of multiple GH families. Lytic polysaccharide monoxygenases (LPMOs) of the AA9 family (formerly GH61) also participate via oxidative mechanisms. White-rot fungi generally have more cellulolytic genes (both hydrolytic and oxidative) and cellulose binding domains (CBM1) relative to brown-rot fungi (Fig. 1). Cellobiohydrolases of families GH6 and GH7 (which cleave cellulose to the disaccharide cellobiose) are correlated with white rot [$r = 0.3$ and 0.6 , respectively, by the independent contrasts method (50)]. Likely involved in boosting cellulase activity (51–54), LPMOs are abundant in white-rot fungi ($r = 0.3$) but reduced in brown-rot fungi ($r = -0.5$). Cellobiose dehydrogenases (family AA3_1), which enhance cellulose degradation (52), are uniformly present in a single copy in all white-rot fungi and absent from the majority of brown-rot fungi (although *Gloeophyllum trabeum* has one copy, and Boletales *Coniophora puteana* and *Serpula lacrymans* each have two copies). Additional cellulolytic families were found in basidiomycetes. For examples, GH5 (containing endo-acting cellulases as well as many other enzymes of differing substrate specificity; Dataset S2), GH12, GH44, and GH45 are expanded in white-rot fungi ($r = 0.2, 0.1, 0.4, 0.5$, respectively) and diminished in brown-rot fungi ($r < -0.2$; for all, see also Dataset S1).

Among the newly sequenced genomes, *G. marginata*, *P. ostreatus*, *B. botryosum*, and *J. argillacea* all possess diverse CAZymes typical of white-rot fungi. *B. botryosum* has 32 genes encoding LPMOs, and three encoding cellobiose dehydrogenases, both more than any other wood decay fungus in our set. *J. argillacea* has 15 genes encoding LPMOs, and one encoding a cellobiose dehydrogenase, both numbers typical of white-rot fungi. A similar pattern is evident when considering families GH6, GH7, and CBM1; *B. botryosum* and *J. argillacea* show a genetic complement similar to white-rot fungi.

Hemicellulolytic and pectinolytic families. Hemicellulose and pectin comprise a variety of linear and branched complex polysaccharides. Hemicellulose includes xylans, xyloglucans, glucuronoxylans, arabinoxylans, mannans, glucomannans, and galactoglucomannans. Pectins include polygalacturonic acid, linear and branched rhamnogalacturonans, and arabinogalactans. Basidiomycetes contain some seven CAZy families that target hemicelluloses, and 11 that target pectins (Table S3). In contrast to the cellulolytic families, there is not a clear dichotomy in which white-rot fungi have more genes encoding hemicellulases and pectinases, and brown-rot fungi have fewer (Dataset S1).

Distribution of Lignin-Degrading Enzymes Blurs the Distinction Between White- and Brown-Rot Fungi. With respect to PODs, there was a clear dichotomy between white-rot fungi, which have various combinations of MnP, LiP, and VP ($r = 0.8$), and brown-rot fungi, which lack PODs ($r = -0.5$). By this measure, the newly sequenced *G. marginata* and *P. ostreatus* resemble typical white-rot fungi with 10 and 9 PODs, respectively. In contrast, *B. botryosum* and *J. argillacea* resemble typical brown-rot fungi in their lack of PODs. *Schizophyllum commune* had previously been characterized as a white-rot fungus (55), but it also lacks PODs. The one class II peroxidase in *J. argillacea* lacks the catalytic Trp and Mn-binding sites, and is therefore classified as a generic peroxidase (56, 57) that is unlikely to directly modify lignin. Affirming the observed genetic complement, extracellular filtrates from *J. argillacea* and *B. botryosum* cultures were unable to oxidize veratryl alcohol or 2,6-dimethoxyphenol, standard substrates for high-oxidation potential PODs (58, 59). According to our phylogeny (Fig. S14), the contraction of ligninolytic PODs in *J. argillacea* may have arisen before its evolutionary separation from *G. trabeum* because both species lack these proteins. However, *G. trabeum* also has a reduced complement of

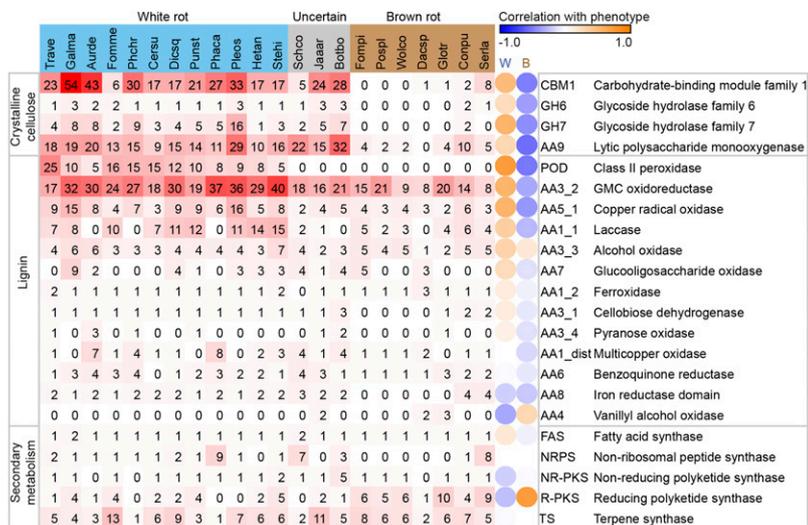


Fig. 1. Lignocellulose-degrading and secondary metabolism in wood-decaying fungi. Organisms use the following abbreviations: Aurde, *Auricularia delicata*; Botbo, *Botryobasidium botryosum*; Cersu, *Ceriporiopsis subvermisporea*; Conpu, *Coniophora puteana*; Dacsp, *Dacryopinax* sp.; Dicsq, *Dichomitus squalens*; Fomme, *Fomitiporia mediterranea*; Fompi, *Fomitopsis pinicola*; Galma, *Galerina marginata*; Glotr, *Gloeophyllum trabeum*; Hetan, *Heterobasidion annosum*; Jaaar, *Jaapia argillacea*; Phaca, *Phanerochaete carnosae*; Phchr, *Phanerochaete chrysosporium*; Pleoc, *Pleurotus ostreatus*; Pospl, *Postia placenta*; Punst, *Punctularia strigosozonata*; Schco, *Schizophyllum commune*; Serla, *Serpula lacrymans*; Stehi, *Stereum hirsutum*; Trave, *Trametes versicolor*; Wolco, *Wolfiporia cocos*. Gene number is shaded red/white, and independent-contrasts correlation of enzyme with rot type is shaded orange/blue. Notice a strict white/brown-rot dichotomy with respect to the lignin-attacking PODs and the CAZymes that target crystalline cellulose (CBM1, GH6, and GH7), and a continuum with other lignin-targeting enzymes.

enzymes attacking crystalline cellulose and is a model system for brown rot (60, 61).

Although PODs have been shown to be important for lignin degradation, numerous other classes of enzymes are capable of degrading, or at least modifying, lignin and about a dozen kinds of enzymes potentially participating in ligninolysis are found in basidiomycetes (Fig. 1). The multicopper oxidases of family AA1 are such an example. Laccases (subfamily AA1_1) may be capable of cleaving lignin bonds in the presence of certain mediators (62) and are more abundant in white-rot fungi than brown-rot fungi (Fig. 1; $r = 0.4$ for white rot; $r = -0.3$ for brown rot). In the cases of *J. argillacea* and *B. botryosum*, no laccase activity was detected in concentrated culture filtrates (63). Nevertheless, the white-rot fungi *P. chrysosporium*, *Phanerochaete carnosae*, and *A. delicata* have no basidiomycete-type laccases *sensu stricto* (17). These three fungi instead have four to eight genes each of the related AA1_dist subfamily of multicopper oxidases (which, predictably, are reduced in brown-rot fungi at 0 to two genes), reflecting the diversity of chemistries used in lignin degradation.

Correlations Between Decay Mode and Secondary Metabolism. Secondary metabolites include polyketides, nonribosomal peptides, and terpenoids, among many other substances that are not considered to be critically involved in an organism's growth, development, and reproduction, but that typically confer some advantage in the never-ending competition with other organisms (64). To assess the diversity of secondary metabolism in basidiomycetes, we characterized fatty acid synthases (FASs), non-ribosomal peptide synthases (NRPSs), polyketide synthases (PKSs), and terpene synthases (TSs). PKSs were additionally subdivided into reducing and nonreducing (R-PKS and NR-PKS), each of which was further divided into subfamilies (Fig. S3). Secondary metabolism enzymes are summarized in the lower panel of Fig. 1.

Wood-decaying basidiomycetes tend to have similar numbers of FAS and NR-PKS genes (approximately one gene each), with the exception of *B. botryosum*, which has five NR-PKS genes. NRPSs vary in gene number (0 to nine genes), with no apparent correlation with lifestyle. TS genes, as well, vary in number (1–13 genes), with no apparent lifestyle correlation.

R-PKSs are expanded in the brown-rot fungi, with all but the phylogenetically basal *Dacryopinax* sp. possessing 4–14 R-PKS genes. In contrast, the white-rot fungi have generally fewer R-PKS genes and many taxa lack them entirely. R-PKS gene number correlates with brown rot (independent-contrasts $r = 0.8$). Although it was previously suggested that secondary

metabolism could play a role in wood decay by the brown-rot fungus *Serpula lacrymans* (20), a widespread pattern of secondary metabolism expansion has not yet been reported for brown-rot fungi in general. The observation that the number of R-PKS genes is expanded in three phylogenetically distinct clades of brown-rot fungi: the Boletales (*S. lacrymans* and *C. puteana*), the Polyporales (*Wolfiporia cocos*, *P. placenta*, and *Fomitopsis pinicola*), and Gloeophyllales (*G. trabeum*), suggests that R-PKSs have a possible role in the brown-rot lifestyle, and that the apparent correlation is not an artifact of phylogenetic sampling. The exact biochemical role of R-PKSs in wood rot in general is unknown. However, it has been suggested that secondary metabolites including certain catechols and quinones can serve as extracellular Fe^{3+} reductants in *G. trabeum*, *S. lacrymans*, *P. placenta*, and *W. cocos*. Together with H_2O_2 , the reduced iron is thought to drive a nonenzymatic Fenton reaction in which highly reactive hydroxyl radicals depolymerize cellulose (20, 65–68).

Secondary metabolism plays a critical role for fungal survival and success, including Basidiomycota (69), and a rich array of secondary metabolism genes has been reported in *Serpula lacrymans* and *Postia placenta* (20), and *Omphalotus olearius* (70). It may be that secondary metabolites, widely considered to confer advantage by inhibiting competing microorganisms, are more important in the ecological niches occupied by brown-rot fungi, compared with white-rot fungi. Indeed, our observation that expansions of R-PKSs are correlated with brown rot in multiple polyphyletic lineages highlights gaps in our knowledge of the mechanisms of wood decay even in well-studied species of Boletales, Polyporales, and Gloeophyllales.

Insights into Diversity of Decay Mechanisms from Phylogenetically Informed Principal-Components Analyses of Decay-Related Gene Families. The expanded sampling of basidiomycete genomes presented here includes species (*B. botryosum*, *J. argillacea*, and *S. commune*) that deviate from the classical models of white rot vs. brown rot, in that they lack PODs (like brown-rot fungi) but possess diverse arrays of enzymes acting on crystalline cellulose (like white-rot fungi). To visualize the diversity of decay chemistries in basidiomycetes, we applied phylogenetically informed principal-components analysis (PCA) (71) to the set of predicted carbohydrate- and lignin-active enzymes (Dataset S1). We hypothesized that organisms should cluster with others of similar nutritional mode, perhaps implying nutritional mode for *B. botryosum* and *J. argillacea*. Fig. 2 shows the wood-decaying fungi plotted on the first two principal components, which together

explain 50% of the variability in the data. For this analysis, we again relied on categorization of fungi as producing either white or brown rot whenever possible. Clear separation of known white- and brown-rotting fungi is seen along PC1. *B. botryosum* and *J. argillacea* group with the white-rot fungi on PC1 and are closest to the model white-rot fungus, *P. chrysosporium*. In contrast, *S. commune* is intermediate between white-rot and brown-rot species along PC1. Both white-rot and brown-rot species are widely distributed along PC2, which suggests heterogeneity in modes of wood degradation within these functional classes. Despite the lack of PODs (Fig. 1), PCA analysis suggests that *B. botryosum* and *J. argillacea* have wood decay properties that are similar to certain white-rot fungi.

Decay Assays in Wood Substrates. To assess the extent to which *B. botryosum* and *J. argillacea* are able to degrade all components of wood, we performed experiments using single-spore isolates of each fungus, on both pine and aspen wood. Both species readily colonized both types of wood, but caused only superficial degradation of the wood surfaces. Nevertheless, in localized areas *B. botryosum* eroded all cell wall layers, indicating degradation and disruption of all cell wall polymers. Hyphae of *B. botryosum* were visible growing in the voids where cell wall degradation had taken place (Fig. 3). The removal of cellulose, hemicellulose, and lignin in these areas is consistent with white rot, whereas in brown rot we would observe residual lignin remaining after a diffuse depolymerization of the cellulose. Similarly, *J. argillacea* degraded a localized area of the wood cells in which all of the cell wall layers were degraded and replaced with the mycelia of the fungus. Once again, complete degradation of all cell wall layers implies all of the wall components have been degraded, as is characteristic of white rot.

We did not include *S. commune* in decay assays as previous studies have shown that this species, although classified as a white-rot species, lacks the ability to degrade lignin appreciably in vitro (55). The *S. commune* genome lacks PODs and has a reduced complement of enzymes bearing cellulose-binding modules (CBM1), but it retains 22 genes encoding LPMOs. Thus, *S. commune* likely has a very different mode of decay than *B. botryosum* and *J. argillacea* (with which it shares the absence of PODs), which is consistent with its isolated position, intermediate between white- and brown-rot species, in the PCA (Fig. 2).

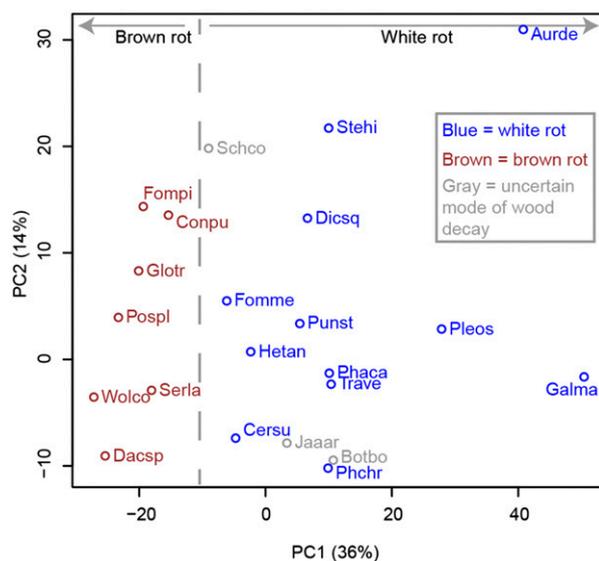


Fig. 2. Wood-decaying basidiomycetes plotted on the first two principal components from phylogenetic PCA of CAZymes (including lignin-related auxiliary activities) of the organisms.

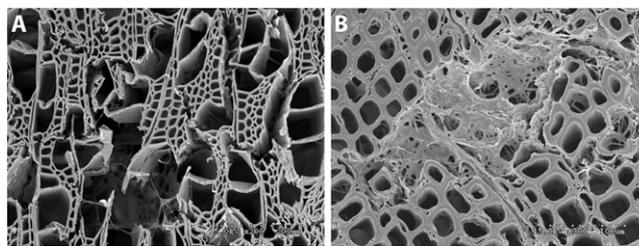


Fig. 3. Wood decay experiments indicating mode of decay by *Botryobasidium botryosum* and *Jaapia argillacea*. (A) Micrograph of *B. botryosum* on aspen wood with vessel, fiber, and parenchyma cell walls degraded. Mycelia are visible growing through the voids. (B) Micrograph of *J. argillacea* on pine showing an area within the wood where the fungus has caused a localized simultaneous decay of the cells. Residual cell wall material and mycelia fill the degraded zone.

Need for a New Classification of Wood Decay Modes. Discussions of the genomic correlates of the white- vs. brown-rot modes of wood decay have typically focused on the lignin-degrading PODs and the hydrolytic and oxidative enzymes involved in attack of crystalline cellulose (17, 23, 25, 72). However, it is also accepted that other enzymes, such as laccases, cellobiose dehydrogenases, and potentially many others, can contribute to white rot (62, 73, 74); accordingly, a database of functional annotations has been dedicated to cataloging lignin-degrading enzymes (49) (Figs. S4 and S5). Our results indicate that the simple dichotomy of white rot vs. brown rot does not adequately reflect the diversity of mechanisms by which wood-rotting fungi obtain nutrition. Specifically, *B. botryosum* and *J. argillacea* show similarities to white-rot fungi in PCA of all predicted carbohydrate- and lignin-active enzymes and can degrade all components of wood, but they do so without the PODs that are a hallmark of white rot. *S. commune* is another putative white-rot fungus (55) that lacks PODs, but it is quite distinct from *B. botryosum* and *J. argillacea* in the PCA (and presumably also in its mode of wood decay). Therefore, we suggest that a more nuanced categorization scheme is needed to describe wood decay by species that degrade all cell wall polymers, including lignin, but lack PODs. As our discovery of the potential role of R-PKSSs in brown rot indicates, other functional considerations beyond lignin-degrading PODs and CAZymes may be important for a biologically descriptive classification of decay modes. Finally, we suggest restricting the term “white rot” to only those fungi that degrade all cell wall polymers through the action of the lignin-degrading PODs in concert with enzymes that attack crystalline cellulose.

Methods

Data Access. Genome assemblies and annotations for the organisms used in this study are available via the JGI Genome Portal MycoCosm (<http://jgi.doe.gov/fungi>; see also Table S1). In addition, the newly sequenced genome assemblies and annotations have been deposited to GenBank under the following accession numbers: *B. botryosum*: AYEP00000000; *G. marginata*: AYUM00000000; *J. argillacea*: AYUL00000000; *P. ostreatus*: AYUK00000000. The versions described in this paper are AYEP01000000, AYUM01000000, AYUL01000000, and AYUK01000000, respectively.

Sequencing, Assembly, and Annotation. The *B. botryosum*, *G. marginata*, and *J. argillacea* genome assemblies were produced using shredded consensus from Velvet-assembled (75) Illumina paired-end data combined with Roche (454) data assembled with Newbler (www.454.com). *P. ostreatus* was sequenced with the Sanger whole-genome shotgun approach and assembled with Arachne (76). All genomes were annotated using the JGI Annotation Pipeline (77), which combines several gene prediction and annotation methods with transcriptomics data, and integrates the annotated genomes into MycoCosm (78), a Web-based fungal resource for comparative analysis.

Protein Sequence Clustering. Predicted protein sequences were clustered using the MCL clustering algorithm (46), with an inflation parameter of 2.0. Two clustering runs were performed: a first one using 63 organisms (33 basidiomycetes, 27 ascomycetes, and 3 from other fungal phyla), which was used for core genes and protein conservation analysis; and a second using 39 organisms (33 basidiomycetes and 4 ascomycetes: *Aspergillus nidulans*, *Pichia stipitis*, *Stagonospora nodorum*, and *Trichoderma reesei*) as outgroups, which was used for generating the phylogenetic tree (see *SI Text* and *Dataset S3* for further details).

Phylogeny. Protein sequences from 183 single-copy clusters were concatenated and multiple-aligned using MAFFT (79) with default parameters, resulting in an alignment with 163,105 amino acid positions. Gblocks (80) was run with the options $t = p$ and $-b4 = 5$ to remove poorly aligned regions, resulting in 38,423 positions. A ML tree was then inferred using RAxML (40) on the Gblocks-trimmed alignment with the PROTGAMMAWAG model, 100 rounds of bootstrapping, and the four Ascomycete organisms *A. nidulans*, *P. stipitis*, *S. nodorum*, and *T. reesei* specified to the program as outgroups. The resulting tree was used for subsequent analyses.

Annotation of Carbohydrate-Active and Auxiliary Redox Enzymes. The carbohydrate-active enzymes (CAZy) and auxiliary redox enzymes (AA) were annotated as in refs. 39 and 49. A manually curated subset of the AA2 family was created, limited to genes predicted to encode high-oxidation potential peroxidases: LiP, MnP, and VP. These are referred to in this work as “POD.”

Annotation of Secondary Metabolism Enzymes. Proteins with an AMP-binding domain (PF00501), a phosphopantetheinyl-binding domain (PF00550), and a condensation domain (PF00668) were designated as NRPS. Proteins with a terpene synthase domain (PF03936) were designated as TS. Proteins with a ketoacyl-synthase (KS) domain (PF00109 and PF02801) were divided into three categories: FAS, NR-PKS, and R-PKS based on their phylogenetic relationships. A gene genealogy was constructed by maximum parsimony analysis in PAUP* 4.0b10 (81) using a ClustalW+ (82) alignment of deduced amino acid sequences. Statistical support for branches was generated by bootstrap analysis with 1,000 pseudoreplications. Putative FASs were grouped in a clade (100% support) that included an Ascomycete KS with significant identity to a FAS from *Aspergillus nidulans* (83). Putative NR-PKSs were grouped in a clade (90% support) that included an Ascomycete NR-PKS involved in the synthesis of a nonreduced polyketide (84). Putative R-PKSs were grouped in three clades (83%, 100%, and 64% support), of which a majority included a ketoreductase (KR) domain (PF08659) (85).

Correlation of Genomic Features and Lifestyle. To infer correlations between genomic features and phenotypes (e.g., repeat content with genome size, or CAZymes with white or brown rot), we used Felsenstein's method of independent contrasts (50) as implemented in the contrast program from Phylip, version 3.62 downloaded from <http://evolution.genetics.washington.edu/phylip> (86).

Phylogenetic PCA. Phylogenetic PCA was implemented using the function *phyl.pca* from the R package *phytools* (www.phytools.org). The algorithm corrects the covariance/correlation matrices for nonindependence among the observations for species, by additionally taking into account the expected covariances/correlations due to pure phylogenetic relatedness of species (71). A matrix of CAZyme gene number in each organism (*Dataset S1*), restricted to the wood decay fungi (Aurde, Botbo, Cersu, Conpu, Dacsq, Discq, Fomme, Fompi, Galma, Glotr, Hetan, Jaaar, Phaca, Phchr, Pleos, Posp, Punst, Schco, Serla, Stehi, Trave, and Wolco), and the ML tree, were used as input.

Wood Decay Assays. Micromorphological observations of degraded aspen (*Populus* sp.) and pine (*Pinus* sp.) wood were used to elucidate the type of decay resulting after inoculation with *B. botryosum* or *J. argillacea*. Physical aspects of decay were investigated using scanning electron microscopy on wood wafers after decay using the same single spore isolate of each fungus that was used for genome sequencing. Dried wood wafers from the sapwood of aspen and pine were cut to $10 \times 10 \times 1$ mm, hydrated to 80–100% moisture, and autoclaved for 60 min at 120 °C. Wood wafers were placed on inoculated Petri plates with malt extract agar (15 g of malt extract, 15 g of agar, 2 g of yeast extract, and 1,000 mL of water). Six plates of each wood type were inoculated with each fungus by placing a 2-mm plug of the assay fungus at the center of a Petri plate 14 d before wafers were added. Wafers were removed 90 d after inoculation and prepared for scanning electron microscopy as previously described (87). Samples were examined and photographed using a Hitachi S3500 N (Hitachi) scanning electron microscope.

Culture Conditions and Enzyme Assays. Standard media included carbon- and nitrogen-starved B3 (88, 89) as well as a more complex medium containing 0.5% (wt/vol) Wiley-mill ground aspen as sole carbon source (90). Culture filtrates were concentrated 6- to 10-fold with 10-kDa spin concentrators (Pall). Protein concentration was determined by the Bradford assay (Sigma-Aldrich). Measurement of LiP, MnP, laccase, and glyoxal oxidase involved oxidation of veratryl alcohol (Sigma-Aldrich) (58), 2,6-dimethoxyphenol (59), 2,2-azonodi-3-ethylbenzothiazoline-6-sulfuric acid (Boehringer), and methyl glyoxal as substrate (91), respectively (see *SI Text* and *Table S4* for further details).

ACKNOWLEDGMENTS. We thank Jill Gaskell (Forest Products Laboratory) for assistance with cultures and enzyme assays. The work conducted by the US Department of Energy (DOE) Joint Genome Institute is supported by the Office of Science of the DOE under Contract DE-AC02-05CH11231. J.D.W. and D.J. were supported by the DOE Great Lakes Bioenergy Research Center (DOE Office of Science Biological and Environmental Research Contract DE-FC02-07ER64494). B.H. is Honorary Professor at the Faculty of Health and Medical Sciences, University of Copenhagen. F.M.'s research group is part of the Laboratory of Excellence for Advanced Research on the Biology of Forest Ecosystems (ANR-11-LABX-0002-01).

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