The gold-standard genome of Aspergillus niger NRRL 3 enables a detailed view of the diversity of sugar catabolism in fungi

Aguilar-Pontes, M. V.; Brandl, Julian; McDonnell, E.; Strasser, K.; Nguyen, T. T. M.; Riley, R.; Mondo, S.; Salamov, A.; Rasmussen, Jane Lind Nybo; Vesth, Tammi Camilla; Grigoriev, I. V.; Andersen, Mikael Rørdam; Tsang, A.; de Vries, R. P.

Published in:
Studies in Mycology

Link to article, DOI:
10.1016/j.simyco.2018.10.001

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
INTRODUCTION

The fungal kingdom is estimated to contain over 1.5 million species (Hawksworth 1991), but only a few species have been studied in depth. In recent years, several hundreds of fungal genomes have been sequenced through different initiatives to gain insights into their biology and the variation within the kingdom (MIT, Arnaud et al. 2012, Grigoriev et al. 2012). Even though sequencing technology has evolved to produce the most complete genome sequence, we are still facing hurdles with respect to gene prediction and functional annotation (Aguilar-Pontes et al. 2014, Watson 2018). Recognizing genes in DNA sequences remains one of the most pressing problems in genome analysis together with the functional annotation of the predicted genes. This can only be improved using a large set of -omics data, literature and human supervision, also known as manual curation. If done properly, the output is a gold-standard genome that can be used to improve the quality of other genomes, especially of related species, to study the evolutionary mechanism that allow them to adapt to their lifestyles and ecological niches. The investments required to generate gold standard genomes go beyond what is feasible in a typical genome sequencing project, as it requires the combined efforts of not only sequencing centres, but also a broad research community that covers many of the biological aspects of fungal life.

Fungi and specifically Aspergilli, can be found in almost all ecosystems. In order to survive in their niches, they have to be able to accommodate their metabolism to the energy source available. In nature, fungi need to recognize the plant biomass components in order to induce the production of the right set of degradative and metabolic enzymes that break down the complex structures forming the plant cell wall into simple molecules. Despite the complexity of the polymers forming the cell wall, the skeleton is mainly formed by simple sugars, such as D-glucose, D-fructose, D-xylose, D-arabinose, D-galactose, D-galacturonic acid and D-rhamnose (Kowalczyk et al. 2014). The ensemble of catabolic pathways that convert these sugars is known as primary carbon metabolism. A previous study investigated the evolution of primary carbon metabolism in A. nidulans and several Aspergilli based on the genome sequence available at that moment, identifying enzyme homologs and additional copies of several genes in some of the species (Flipphi et al. 2009). However, a recent study indicated that extra copies of an enzyme or a catabolic pathway does not necessarily affect the catabolic efficiency of the species under specific growth conditions, but correlates with the phylogenetic relationship between species (de Vries et al. 2017). However, a positive correlation was found between the presence of a gene predicted to encode a catabolic enzyme and their ability to grow on a specific carbon source (de Vries et al. 2017).

In this study, a network of reactions of primary metabolism based on the Aspergillus niger NRRRL 3 gold-standard genome (Genozymes 2009) (manuscript in preparation) was generated and used to find orthologous genes and pathways involved in the catabolism of monosaccharides in a set of closely related fungal species (Fig. 1). The main focus was to evaluate whether there is a link between genome content and growth abilities. Our aim here is to study the genome content related to primary carbon
metabolism to identify key enzymes or reactions that explain growth under specific conditions. The advantage of using a gold-standard genome, with telomere-to-telomere chromosomes and manually curated gene models, as a reference for this study is that it significantly reduced the risk of missing genes due to gaps in the genome sequence and errors in electronic gene calling.

MATERIALS AND METHODS

Whole genome phylogeny

Whole genome phylogeny was performed among the 28 species selected (Saccharomyces cerevisiae S288C, Neurospora crassa OR74A, Trichoderma reesei QM 6a, Talaromyces marneffei ATCC 18224, Talaromyces stipitatus ATCC 10500, Penicilliosis zonata CBS 506.65, Penicillium digitatum PHI 26, P. chrysogenum CBS 307.48, P. rubens Wisconsin 54-1255, Aspergillus glaucus CBS 516.65, A. wentii CBS 141137, A. clavatus NRRL 1, A. novofumigatus CBS 117520, A. fumigatus AT293, A. fischeri NRRL 181, A. campestris IBT 26561, A. terreus NIH 2624, A. flavus NRRL 3357, A. oryzae RIB40, A. nidulans FGSC A4, A. sydowi CBS 593.65, A. versicolor CBS 795.97, A. aculeatus ATCC 16872, A. carbonarius ITEM 5010, A. brasilensis CBS 101740, A. niger NRRL 3, A. luchuensis CBS 106.47 and A. tubingensis CBS 134.48). The tree was built using 200 bidirectional best-blast hits (BBH), which were aligned using mafft V7.221 (Katoh & Standley 2013) with default parameters. Uninformative/ambiguous sites were removed from the alignment using Gblocks v0.91b (Nielsen et al. 1997) with parameters –t = p –e = gb –b4 = 5. The maximum likelihood tree was built using FastTree v2.1.9 with parameters –gamma –wag.20 rate categories were used during phylogeny reconstruction. This phylogenetic tree was visualized using R language and environment v.
Table 1. List of species used in this study.

<table>
<thead>
<tr>
<th>Species</th>
<th>Strain</th>
<th>Section</th>
<th>Species abbreviation 1</th>
<th>Number of genes</th>
<th>Assembly length (Mb)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Saccharomyces cerevisiae</em></td>
<td>S288C</td>
<td>Sacce1</td>
<td></td>
<td>6575</td>
<td>12</td>
<td>(Goffeau et al. 1996)</td>
</tr>
<tr>
<td><em>Neurospora crassa</em></td>
<td>OR74A</td>
<td>Neur2</td>
<td></td>
<td>10785</td>
<td>41</td>
<td>(Galagan et al. 2003)</td>
</tr>
<tr>
<td><em>Trichoderma reesei</em></td>
<td>OM 6a</td>
<td>Trire2</td>
<td></td>
<td>12136</td>
<td>36</td>
<td>(Martinez et al. 2008)</td>
</tr>
<tr>
<td><em>Talaromyces marneffei</em></td>
<td>ATCC 18224</td>
<td>Talaromyces</td>
<td>Talm1_2</td>
<td>10638</td>
<td>29</td>
<td>(Nierman et al. 2015)</td>
</tr>
<tr>
<td><em>T. stipitus</em></td>
<td>ATCC 10500</td>
<td>Talaromyces</td>
<td>Tals1_2</td>
<td>10252</td>
<td>36</td>
<td>Unpublished</td>
</tr>
<tr>
<td><em>Penicillioopsis zonata</em></td>
<td>CBS 506.65</td>
<td>Aspzo1</td>
<td></td>
<td>9886</td>
<td>29</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>Penicillum digitatum</em></td>
<td>PHI 26</td>
<td>Penicillium</td>
<td></td>
<td>9118</td>
<td>29</td>
<td>(Marcel-Houben et al. 2012)</td>
</tr>
<tr>
<td><em>P. chrysogenum</em></td>
<td>CBS 307.46</td>
<td>Chrysogena</td>
<td>Pench1</td>
<td>11396</td>
<td>31</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>P. rubens</em></td>
<td>Wisconsin 54-1255</td>
<td>Chrysogena</td>
<td>PenchWisc1_1</td>
<td>13671</td>
<td>32</td>
<td>(van den Berg et al. 2008)</td>
</tr>
<tr>
<td><em>Aspergillus glaucus</em></td>
<td>CBS 516.65</td>
<td>Aspergillus</td>
<td></td>
<td>11277</td>
<td>28</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>A. wentii</em></td>
<td>CBS 141173</td>
<td>Cremei</td>
<td>Aspwe1</td>
<td>12442</td>
<td>31</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>A. clavatus</em></td>
<td>NRRL 1</td>
<td>Clavati</td>
<td>Aspcl1</td>
<td>9121</td>
<td>28</td>
<td>(Fedorova et al. 2008)</td>
</tr>
<tr>
<td><em>A. novofumigatus</em></td>
<td>CBS 117520</td>
<td>Fumigati</td>
<td></td>
<td>11549</td>
<td>32</td>
<td>(Kjaerbolling et al. 2018)</td>
</tr>
<tr>
<td><em>A. fumigatus</em></td>
<td>A2933</td>
<td>Fumigati</td>
<td>Aspft1</td>
<td>9781</td>
<td>29</td>
<td>(Nierman et al. 2005)</td>
</tr>
<tr>
<td><em>A. fischeri</em></td>
<td>NRRL 181</td>
<td>Fumigati</td>
<td>Neo1</td>
<td>10406</td>
<td>33</td>
<td>(Nierman et al. 2005)</td>
</tr>
<tr>
<td><em>A. campesiris</em></td>
<td>IBT 28561</td>
<td>Candidi</td>
<td>Aspcam1</td>
<td>9764</td>
<td>28</td>
<td>(Kjaerbolling et al. 2018)</td>
</tr>
<tr>
<td><em>A. terreus</em></td>
<td>NIH 2624</td>
<td>Terrei</td>
<td></td>
<td>10406</td>
<td>29</td>
<td>(Arnaud et al. 2012)</td>
</tr>
<tr>
<td><em>A. flavus</em></td>
<td>NRRL 3357</td>
<td>Flavi</td>
<td></td>
<td>12604</td>
<td>37</td>
<td>(Payne et al. 2006)</td>
</tr>
<tr>
<td><em>A. oryzae</em></td>
<td>RIB40</td>
<td>Flavi</td>
<td></td>
<td>12030</td>
<td>38</td>
<td>(Machida et al. 2005)</td>
</tr>
<tr>
<td><em>A. nidulans</em></td>
<td>FGSC A4</td>
<td>Nidulantes</td>
<td>Aspnid1</td>
<td>10680</td>
<td>30</td>
<td>(Galagan et al. 2005)</td>
</tr>
<tr>
<td><em>A. sydowii</em></td>
<td>CBS 593.65</td>
<td>Nidulantes</td>
<td>Aspsy1</td>
<td>13620</td>
<td>34</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>A. versicolor</em></td>
<td>CBS 583.65</td>
<td>Nidulantes</td>
<td>Aspve1</td>
<td>13228</td>
<td>33</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>A. aculeatus</em></td>
<td>ATCC 16872</td>
<td>Nigri</td>
<td>Aspac1</td>
<td>10845</td>
<td>35</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>A. carbonarius</em></td>
<td>ITEM 5010</td>
<td>Nigri</td>
<td>Aspca3</td>
<td>11624</td>
<td>36</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>A. brasiliensis</em></td>
<td>CBS 101740</td>
<td>Nigri</td>
<td>Aspbr1</td>
<td>13000</td>
<td>36</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>A. niger</em></td>
<td>NRRL 3</td>
<td>Nigri</td>
<td>Asnrl_NRRL3_1</td>
<td>11846</td>
<td>35</td>
<td>Unpublished</td>
</tr>
<tr>
<td><em>A. luchuensis</em></td>
<td>CBS 106.47</td>
<td>Nigri</td>
<td>Aspcl1</td>
<td>13530</td>
<td>37</td>
<td>(de Vries et al. 2017)</td>
</tr>
<tr>
<td><em>A. tubingensis</em></td>
<td>CBS 134.48</td>
<td>Nigri</td>
<td>Aspt1</td>
<td>12322</td>
<td>35</td>
<td>(de Vries et al. 2017)</td>
</tr>
</tbody>
</table>

The order of the species follows the taxonomic organization in the phylogenetic tree (Fig. 2).

1 The species abbreviations correspond to JGI acronyms used as species and genome released unique identifiers in the portal. This identifier is used as species identifier in the heatmap figures.

3.4.0 (R Core Team 2017) with the package ggplot2 v. 1.8.2 (Yu et al. 2017) from ggplot2 v. 2.2.1 (Wickham 2009).

Protein quality assessment

Protein quality assessment was performed using BUSCO v3 (Simao et al. 2015) with default parameters and specific lineage database accordingly (Aspergillus, Penicillium, Penicillioopsis and Talaromyces species against euromyciomes_odb9 database, *N. crassa* and *T. reesei* against sordariomycetes_odb9 database and *S. cerevisiae* saccharomyceta_odb9 database).

Protein functional annotation

Protein functional annotation of selected species was downloaded from the JGI Mycocosm Portal (Table 1). Exclusively InterPro and Pfam domains (Quevillon et al. 2005) with E-value >1e^{-15}, KEGG database information (Kanehisa et al. 2006) and SignaIP annotation (Nielsen et al. 1997) was used. Additionally, *S. cerevisiae*, *N. crassa*, *T. reesei* and *A. nidulans* functional information was obtained from the SGD database (Cherry et al. 2012), Ensembl Fungi Biomart release 38 (Kinsella et al. 2011), (Benocci et al. 2018) and the AspGD database (Cerqueira et al. 2014), respectively.

Protein profiling

Gene families (clusters) were downloaded from JGI Mycocosm Portal (Grigoriev et al. 2014) https://genome.jgi.doe.gov/clm/run/fungi-2016-08.1352. Clusters were predicted by Blast (Altschul et al. 1990) E-value 1e^{-5} and MCL inflation parameter =2 (Enright et al. 2002). Clusters with only one protein assigned were removed from the original data set. In total, 112 gene clusters containing *A. niger* NRRL3 proteins of interest were selected. Amino acid sequences of selected species were downloaded from the JGI Mycocosm Portal (Table 1). Alignment of the amino acid sequences of the proteins included in the clusters was performed using mafft V7.221 (Katoh & Standley 2013) with default parameters. Alignments were manually curated and nucleotide sequences of split genes were fixed where possible, otherwise the protein sequence was removed from the alignment (Supplementary file...
X1). A Neighbor joining tree was built using MEGA-CC (Kumar et al. 2012) with complete deletion and bootstrap 500. Phylogenetic trees were inspected manually and rooted to S. cerevisiae where possible. Proteins included in a monophyletic tree with an A. niger NRRL3 proteins will be considered as NRRL3 orthologs. Close orthologs of a NRRL3 protein will be defined as group of proteins included in a monophyletic tree after a gain or loss event where no NRRL3 protein is present. These are identified with the closest NRRL3 protein id and the suffix “like”. A. niger protein functional information was used to assign function to ortholog groups within a cluster. Groups with functional annotation not related to monosaccharides metabolism were removed from the final set when supported by more than one protein. If no NRRL3 protein was present in the group, curated database information of other species was used (Supplementary file X2). If more than one transcript per protein was included in the tree, they were counted as one (Supplementary file X3). Membership in a group was used to determine whether a protein was conserved across the selected species. If a protein is found at least once in all members or all members of an organism subset (e.g. section Nigri), it is considered conserved. A protein was considered specific to an organism subset if it was found in at least one organism of the subset, but not in any organisms outside the subset. Heatmaps were generated using R language and environment with the package ComplexHeatmap v. 1.14.0 (Gu et al. 2016). Columns are ordered according to the phylogenetic tree and rows follow the order of the reactions in the pathway. Growth graphs were generated using Adobe Illustrator CC.

Growth profiling on different monosaccharides

For growth profiling, all strains were grown on MM (de Vries et al. 2004) with 33 different carbon sources (http://www.fungrowth.org/). Growth was performed at 30 °C for all Aspergillus and 25 °C for the other species. Growth was continued until the largest colony of a species set almost reached the edge of the plate. Growth per species was scored from 0 when there is no visible growth to 10 when maximum growth among all carbon sources has been reached. Growth profiles containing monosaccharides and disaccharides (de Vries, et al.) were selected for this study (Supplementary file X4). Media with no carbon source was used as a control. If growth on a specific carbon source is the same as with no carbon source, it is considered no growth.

RESULTS

Phylogenetic relationships and proteome assessment

To provide an overview of the relationship among the selected species (Table 1) a genome-wide phylogeny was conducted (Fig. 2A). The constructed tree supports the results described before (Kocsube et al. 2016). Members of the section Nigri are in a single clade close to section Nidulantes that also appears as a single clade. Section Flavi (A. oryzae and A. flavus) are placed close to the representative of section Terri with section Candidi as an outgroup. Section Fumigati and section Clavati are in another clade with A. wenti from section Cremei as a close relative. The genus Penicillium sections Chrysogena and Penicillium are placed close to the related species Penicilliosis zonata (previously Aspergillus zonatus (Kocsube et al. 2016)), T. reesei and N. crassa are at the base of the tree with S. cerevisiae at the root.

The genomes used in this study have been sequenced over the years by different consortia and technologies. S. cerevisiae was the first fungal genome published in 1996 (Goffeau et al. 1996) while A. campesiris was published in 2016 (Kjaerbolling et al. 2018) sequenced with the latest technology PacBio RS. Hence the quality of assembled genomes and annotation can vary substantially. We used BUSCO (Simao et al. 2015) to evaluate the completeness across their predicted proteomes. The average of complete proteins is higher than 95 % in most species with the exception of A. carbonarius, where only 88 % of the genomes are complete with more than 8 % of the core proteins missing. The proportion of the proteomes that are duplicated comprise approx. 1 % except for S. cerevisiae, N. crassa, Talaromyces species and A. carbonarius that varies between 5 – 10 %. With the exception of A. carbonarius, the genomes with the higher number of missing proteins also contain a higher number of fragmented proteins. High numbers of fragmented proteins were observed regardless the genus, technology, assembler or automatic gene calling methodology. Species with more than 150 fragmented proteins (A. oryzae, A. flavus, A. terreus, P. digitatum) were removed from the analysis (Fig. 2B).

Complete genomic sequences from diverse phylogenetic lineages reveal notable increases in genome complexity from prokaryotes to multicellular eukaryotes (Lynch & Conery 2003). However, the genome size of an organism varies from species to species and is not proportionally correlated with organismal complexity. In our dataset, the smallest genome is 12 Mb and the largest 41 Mb, corresponding to S. cerevisiae and N. crassa respectively, but the N. crassa genome only contains twice the number of genes of the S. cerevisiae genome. With the exception of S. cerevisiae and N. crassa, more than 95 % of the predicted proteins were included in the gene families downloaded from the JGI Mycocosm portal (Grigoriev et al. 2014) (Fig. 2C).

Genome content related to primary carbon metabolism

In contrast to the most accepted theory (Gregory 2001), the present study shows that genome size and gene content are an indication of primary carbon metabolism complexity (Supplementary Fig. 5). In general, S. cerevisiae lacks several of the enzymes associated with primary carbon metabolism predicted in A. niger. In some cases, entire pathways are missing, even though growth has been described (Oliva Neto et al. 2014). Therefore, in the following sections we will describe the prevalence of orthologous genes in the different species without considering S. cerevisiae except for special cases. Starting with glycolysis and acid production (glyoxylate, tricarboxylic and d-gluconic acid) from glycolytic products, the pathways have been ordered according to the step in which the final product enters glycolysis and to the number of carbon atoms in the main substrate: maltose, sucrose, β-mannose, β-galactose, β-galacturonic acid, β-rhamnose, pentose catabolic and pentose phosphate pathway. In each case, a brief description of the pathway with the EC numbers of each enzymatic reaction and common protein names used in A. niger will follow a deep analysis of the relationship between phylogeny, genome content and growth.
abilities. The ortholog groups will be referred to by the protein number of the *A. niger* NRRL 3 gene present in the group. If no NRRL 3 gene is present, the group will be referred to by the closest NRRL 3 paralog, followed by ‘-like’. Despite ‘after’ and ‘before’ not being the appropriate phylogenetic terms, we will use them to refer to moments in evolution when proteins have been gained or lost between two groups. Due to the limited number of species from each clade in this study we cannot determine when this exactly happened, e.g. in glycolysis, NRRL3_11729_like appears in members of the genus *Talarnomyces* and is lost after section *Fumigati*. Meaning that species from clades after section *Fumigati* branched off, resulting in sections *Candidi*, *Nidulantes* and *Nigri* having lost this ortholog.

### Glucose and fructose catabolism

D-Glucose is the preferential monomeric carbon source for most microorganisms. Although fungi rarely find free high concentration of D-glucose in their environment, it is the major component of the plant cell wall ([Kowalczyk et al. 2014](#)). Therefore, it is common that all species contain at least one enzyme per reaction for D-glucose catabolism (Fig. 3).

This first step in the glycolysis in the conversion of D-glucose into D-glucose 6-phosphate by two different enzymes, the hexokinase (Hxk, EC 2.7.1.1) ([Panneman et al. 1998](#)) and the glucokinase (Glk: EC 2.7.1.2) ([Panneman et al. 1996](#)). Isomerization of D-glucose 6-phosphate by glucose 6-phosphate isomerase (PfkA, EC 2.7.1.11) produces fructose 6-phosphate. This compound can be obtained from D-fructose through fructokinase reaction by hexokinase enzymes exclusively ([Panneman et al. 1998](#)). A kinase reaction catalyzed by the 6-phosphofructokinase (PhkA, EC 2.7.1.11) converts D-fructose 6-phosphate into D-fructose 1,6-bisphosphate ([Habison et al. 1983](#)). The reverse reaction, is catalysed by the D-fructose 1,6-bisphosphatase (FbpA, EC 3.1.3.11). Both reactions are strongly regulated by the accumulation of D-fructose 2,6-bisphosphate, which activates PhkA and inhibits FbpA ([Harmsen et al. 1992](#), [Ruijter & Visser 1999](#), [Poulsen et al. 2005](#), [Upadhyay & Shaw 2007](#)).
2009), we found only one cluster containing a glucokinase and tested species. Compared to a previous study (Flipphi et al. 2010), we found only one cluster containing a glucokinase and D-fructose, out of which only two have catalytic function.

HxkA (NRRL3_05100) is present in all species while its paralog, NRRL3_11729 has two main groups. An orthologous gene present in P. rubens, A. nidulans, A. sydowii and section Nigri genomes and a close orthologous group that appears in members of the genus Talaromyces and got lost after section Fumigati. Three different Glk groups were identified in the phylogeny. An orthologous gene of A. niger GlkA (NRRL3_03068) is present in all species. A second sequence (NRRL3_03068_like_1) is present in the genome of the Talaromyces species, section Fumigati, A. sydowii and A. carbonarius. A third Glk protein (NRRL3_03068_like_2) is also present in these species except for the Talaromyces species.

Proteins from two different clusters have been assigned to Fba activity. The ortholog of A. nidulans FbaA, NRRL3_05672 (FbaA) is present in all species (Roumelioti et al. 2010) in a single cluster. The second cluster contain two orthologous groups NRRL3_00967 and NRRL3_08838, respectively. NRRL3_00967 is present in all species except T. reesei, and a NRRL3_00967_like group is formed from genes of sections Cremei, Nidulantes and several species from section Nigri. A similar distribution is observed for NRRL3_08838, including members from the genus Penicillium and T. reesei. Iso-enzymes assigned to Pgm activity belong two different clusters. Both PgmA (NRRL3_07072) and the second enzyme NRRL3_03100 are present in all species. A NRRL3_03100 like orthologous gene was present in P. zonata, A. clavatus and section Fumigati.

Due to the importance of the pathway metabolizing D-glucose and D-fructose and the absence of orphan reactions, we predicted positive growth for all species on these sugars, which was confirmed by our growth data. T. reesei and A. tubingensis grew better on these substrates compared to other carbon sources.
than any of the other species. Remarkably, *P. zonata* grew below average on both substrates despite the genome content not showing major differences with respect to the genes related to glycolysis compared with the rest of the species.

**Glyoxylate and tricarboxylic acid cycle metabolism**

The final product of glycolysis is metabolized further through the tricarboxylic acid (TCA) and the glyoxylate cycles. The glyoxylate cycle was described as a modified TCA cycle (Kornberg & Madsen 1958) with which it shares activities (Kunze et al. 2006). The partial parallelism between both cycles requires that identical enzymatic activities have to participate independently in different metabolic pathways, which is accomplished in most cases by paralogous proteins that are differently compartmentalized in the cell. The TCA cycle enzymes are mainly localized in the mitochondria while the glyoxylate cycle enzymes are located both inside and outside the peroxisome. The glyoxylate cycle allows cells to utilize C2 carbon sources, e.g. ethanol and acetate, when other carbon sources are not available and it further allows the cell to produce carbohydrates through gluconeogenesis from acetyl-CoA. The glyoxylate cycle bypasses the reactions catalysed by isocitrate dehydrogenase and 2-oxoglutarate complex. Two molecules of acetyl-CoA enter the glyoxylate cycle during each turn, while only one enters the TCA cycle. Bypassing the TCA cycle conserves carbon atoms for gluconeogenesis while simultaneously diminishing the flux of electrons into respiration (Hynes et al. 2007). Pyruvate produced through glycolysis can be converted into acetyl-CoA through the pyruvate dehydrogenase complex (EC1.2.1.−) in the mitochondria or into oxaloacetate by pyruvate carboxylase (PycA, EC 6.4.1.1) (Fig. 4). The pyruvate dehydrogenase complex involves three enzymatic reactions with

![Fig. 4. Glyoxylate and TCA cycles heatmap abundance of A. niger orthologous proteins in the glyoxylotic and TCA pathways. The legends are the same as that of Fig. 3. MdhA_P: peroxisomal MdhA and MdhA_M: mitochondrial MdhA.](image-url)
independent enzymes associated to them: the pyruvate dehydrogenase alpha and beta subunits (PdaA), the dihydrodipamide S-acetyltransferase and the lipooamide dehydrogenase (LpdA). Another source of acetyl-CoA is the reaction catalysed by the acetyl-CoA synthetase (Acu, EC 6.2.1.1) from coenzymeA and acetate. The acetate used as substrate in this reaction can be provided by oxalacetate acetylhydrolase (Oah, EC 3.7.1.1) after converting oxaloacetate into oxalate (Ruijter et al. 1999, Narayanany et al. 2009).

The glyoxylate and TCA cycles share three enzymatic reactions, with different paralogs for malate dehydrogenase and citrate synthase, but the same enzyme for aconitate.

Malate dehydrogenase (Mdh, EC 1.1.1.37) catalyses the reversible conversion between malate and oxaloacetate (McAllister-Henn et al. 1995). Oxaloacetate is converted into citrate by citrate synthase (Cit, 2.3.3.1). The citrate produced in the glyoxylic cycle its transported to the mitochondria to be converted first into cis-aconitate and finally to isocitrate (α-three-isocitrate) by aconitate hydratase (Aco, EC 4.2.1.3) that catalyzes both steps. Isocitrate relocates to the peroxisome to continue the glyoxylate cycle.

In the peroxisome, during the glyoxylate cycle, isocitrate lyase (EC 4.1.3.1) will breakdown isocitrate into glyoxylate and succinate, which then enter the TCA. Finally, glyoxylate will be used as substrate together with acetyl-CoA for malate synthase (EC 2.3.3.9) to produce malate and coenzymemeA.

In the mitochondria, during the TCA cycle, isocitrate is converted into 2-oxoglutarate by two different isocitrate dehydrogenase reactions, with different cofactors (NADP, EC 1.1.1.42 and NAD, EC 1.1.1.41). The 2-oxoglutarate complex converted coenzymeA to 2-oxoglutarate to produce succinylCoA. This complex requires three different enzymes, a mitochondrial 2-oxoglutarate dehydrogenase (EC 1.2.4.2), a dihydrolipoxamide succinyl-transferease (EC 2.3.1.61) and the dihydrolipoyl dehydrogenase (EC 1.8.1.4). Succinate-CoA ligases (GTP as cofactor, EC 6.2.1.4 and ATP as cofactor 6.2.1.5) catabolize the conversion of succinyl-CoA into succinate. Succinate dehydrogenase (EC 1.3.5.1) oxidizes succinate into fumarate. Finally, the last step in the TCA cycle is the conversion of fumarate into malate by the fumarate hydratase (FumR, EC 4.2.1.2).

Most of the enzymatic reactions have multiple isoenzymes assigned to them. Only Pyca (NRRL3_08073), the peroxisomal malate synthase (NRRL3_03733), isocitrate lyase (NRRL3_02395) and the mitochondrial FumR (NRRL3_03113) and MdhA_M (NRRL3_04395) are present as a single enzyme in all genomes, some of them are present as more than one copy.

Within the pyruvate dehydrogenase complex, pyruvate dehydrogenase has two subunits, alpha and beta. The alpha subunits, PdaA (NRRL3_04970) and NRRL3_09769 belong to the same cluster. PdaA is present in all species except in A. nidulans while NRRL3_09769 is missing in N. crassa, T. reesei and P. zonata. The beta subunit containing orthologs for all species. Enzymes from two different clusters have been assigned to dihydrolipomamide S-acetyltransferease activity, with the A. niger genes NRRL3_05302 and NRRL3_04398 assigned to them, and orthologs for both are present in all species. The last component of the complex, LpdA (NRRL3_04756), is present in all species. Acetyl-CoA synthase, AcuA (NRRL3_07795) is also present in all species, but its paralog (NRRL3_03516) is missing in A. aculeatus. A third enzyme, NRRL3_03516_like is present in A. wenti, A. fischeri, A. campestris A. versicolor, A. aculeatus and A. tubingensis. Even though in the network only one protein was assigned to the oxaloacetate dehydrogenase reaction, OahA (NRRL3_06354), the orthology analysis shows two additional paralogous groups (NRRL3_04875 and NRRL3_06354_like). All genomes contain at least one protein assigned to this reaction. After T. stipitis branched off multiple sequences are found reaching the higher number of paralogs in section Nigri.

In glyoxylate cycle, three isoenzymes have been assigned to the malate dehydrogenase reaction belonging to two different clusters. MdhA_P (NRRL3_03570) is present in all species, except A. campestris. A second enzyme in the same cluster, NRRL3_09556 is present only in section Nigri, A. nidulans, A. wenti and the Penicillium species. The third group of enzymes from a different cluster, orthologs of NRRL3_08866, is present in all species except A. luchuensis and A. fischeri. A NRRL3_08866_like group containing genes from A. wenti, section Nidulantes, A. carbonarius and A. tubingensis was also identified.

Initially, two citrate synthases assigned in the network were identical, NRRL3_02449 and NRRL3_11764, but according to in house data they do not participate during glyoxylate production. Nevertheless, A third paralog was identified through orthology. NRRL3_00288 appeared after genus Talaromyces split off and it is only missing in A. aculeatus.

In the TCA cycle, citrate synthase is assigned to two mitochondrial enzymes, CitA (NRRL3_00547) and McsA (NRRL3_03739) that belong to the same cluster and are present in all species. NADH+-dependent isocitrate dehydrogenase (NRRL3_05263) is also present in all species. This cluster also contains NRRL3_05263_like sequences from S. cerevisiae and A. campestris that group separately. NADH+-dependent isocitrate dehydrogenase isoenzymes (NRRL3_10706 and NRRL3_11176) that belong to the same cluster, are present in all species.

Interestingly, one enzyme of each component of the 2-oxoglutarate dehydrogenase complex is present in almost all species, NRRL3_07854, NRRL3_09217 (missing in T. marneffei) and LpdA (NRRL3_04756). A second 2-oxoglutarate dehydrogenase NRRL3_11728 and a dihydrolipomamide S-succinyl transferase NRRL3_11727 are only present in A. versicolor and some members of section Nigri.

Succinate-CoA ligases NRRL3_06528 and NRRL3_00603 belong to different clusters. Both enzymes are present in all species. In addition, a NRRL3_06528_like group contains a T. reesei and A. sydowii sequence, and these species also contain a NRRL3_06003_like sequence together with P. zonata, Penicillium species, A. wenti, A. clavatus, species from section Fumigatus and A. campestris.

Succinate dehydrogenases assigned in the network belong to several clusters. All species contain between six and eight paralogs encoded in their genome, section Nigri contain up to ten paralogs.

Beside production of different acids, the intermediate metabolites of both cycles are used to produce different amino acids essential for the fungus to survive in the environment. Since growth on the pyruvate precursors α-glucose and α-fructose was possible, we can predict that all species have functional TCA and glyoxylate cycles.

α-Gluconate metabolism

In the presence of α-glucose, some fungi will produce gluconate and its acid form α-gluconic acid as the primary overflow metabolite under non-limiting growth on glucose (Shindia et al.)
Metabolism of the disaccharides maltose and sucrose

Maltose is a disaccharide formed by two molecules of α-D-glucose with a 1,4-glucoside linkage. Through hydrolysis, α-glucosidase produces two molecules of D-glucose that enters glycolysis. α-glucosidase or maltase (EC 3.2.1.20) belongs to CAZy families GH13 and GH31 (Lombard et al. 2014) (Fig. 6). Seven different A. niger proteins have been assigned in the network. Enzymes from family GH31, AgdA (NRRL3_07700), AgdB (NRRL3_05254), AgdE (NRRL3_00475), AgdF (NRRL3_10609) and AgdG (NRRL3_04254) belong to four different clusters (Kimura et al. 1992, Nakamura et al. 1997). Enzymes from family GH13, AgdD (NRRL3_01282) and NRRL3_05201 belong to a unique cluster. All species contain more than one protein in their genome from family GH31 from different clusters. Within family GH13, NRRL3_05201 ortholog is present in all species of the Eurotales. The NRRL3_01282 like group is mostly missing in section Nigri, while AgdD (NRRL3_01282) is specific for section Nigri.

All species in this study contain more than one α-glucosidase in their genome, which match their ability to grow on maltose as sole carbon source. T. stipitatus, A. fischeri and A. niger grew better on maltose than on α-glucose. S. cerevisiae is not able to grow on α-maltose which correlates with the presence of only two α-glucosidases in its genome, AgdE and AgdD orthologs. Other than this example, there is no correlation between the number of enzymes encoded and their ability to grow on maltose.

Succrose is a disaccharide of D-glucose and D-fructose and its hydrolysis is catalysed by β-D-fructofuranoside fructohydrolase (EC 3.2.1.26) belonging to CAZy family GH32 (Lombard et al. 2014), also known as invertase (Fig. 7). The catalytic reaction releases two monomers, an α-D-glucose and a β-D-fructose that both enter glycolysis through the enzymatic reactions catalyzed by hexokinases (HxkA and NRRL3_11729) and glucokinases (Gik), where the latter only acts on α-D-glucose.

There are three invertases (SucA-C) assigned to A. niger sucrose degradation (Boddy et al. 1993, Wallis et al. 1997), all of which belong to the same cluster. Invertases SucB (NRRL3_03595) and SucC (NRRL3_11821) appeared firstly in T. stipitatus genome. SucA (NRRL3_11752) appeared when Penicillium species
SucC is only present in *T. stipitatis*, Penicillium species, *A. brasiliensis* and *A. niger*, while SucB is present in all species except *P. zonata*, *A. clavatus* and *A. campestris*. SucA is missing in *A. clavatus*, *A. campestris*, *A. nidulans* and section *Fumigati*. In summary, *P. zonata*, *A. clavatus* and *A. campestris* lack all three enzymes, section *Fumigati* only contains SucB, section *Nidulantes* and *Nigri* contain mainly SucA and SucB, while *Penicillium* species contain all three. All species show different degrees of growth on sucrose. *T. stipitatis*, *A. wentii*, *A. brasiliensis* and *A. luchuensis* grew better on this disaccharide than on the monosaccharides, D-glucose and D-fructose. *T. marneffei* showed reduced growth on sucrose compared to D-glucose and D-fructose. *Trichoderma reesei* is known for lacking invertases in its genome; however, it is able to grow when invertases from other species are heterologously produced (Berges et al. 1993), which corroborates the use of the resulting monosaccharides as substrates of glycolysis. On the other hand, *S. cerevisiae* and *N. crassa* showed growth on sucrose although they miss all three ortholog of genes identified in *A. niger* NRRL 3, which showed the sequence diversity within the CAZY family or a different mechanism to degrade sucrose.

### α-Mannose metabolism

α-α-Mannose can be metabolized through glycolysis or utilized for the formation of glycoproteins through the production of GDP-α-α-mannose (Fig. 8). α-α-Mannose is converted to α-α-mannose-6-phosphate by Hxk (see glycolysis metabolism section) and it is linked to glycolysis through mannose-6-phosphate isomerase (PmiA, EC 5.3.1.8) (Ruijter & Visser 1999, Upadhyay & Shaw 2006) that converts α-mannose-6-phosphate in D-fructose-6-phosphate.

To produce GDP-α-α-mannose, phosphomannomutase (PmmA, EC 5.4.2.8) converts α-mannose into α-α-mannose-1-phosphate that is further converted by the mannose-1-phosphate guanylyltransferase (EC 2.7.7.13) to GDP-α-α-mannose.

PmiA (NRRL3_11229) and its ortholog NRRL3_07971 and PmmA (NRRL3_10685) are present in all species. Two clusters encoding mannose-1-phosphate guanylyltransferase were found. All species contain enzymes from these two clusters (NRRL3_07837 and NRRL3_09951) except *A. carbonarius* that contains also a NRRL3_07837_like protein.

In general, all species show growth on α-mannose similar to D-glucose, except *T. marneffei* that showed highly reduced growth compared to D-glucose.

### α-Galactose metabolism

In *A. niger* α-galactose can be metabolized through three different pathways (Fig. 9). The Leloir pathway and the oxidoreductive pathway final products of which enter glycolysis as D-fructose-6-phosphate or D-glucose-6-phosphate, and the non-

---

**Fig. 6. Maltose heatmap** abundance of *A. niger* orthologous proteins in the maltose catabolic pathway. The legends are the same as that of Fig. 3.

**Fig. 7. Sucrose heatmap** abundance of *A. niger* orthologous proteins in the sucrose catabolic pathway. The legends are the same as that of Fig. 3.
phosphorylated DeLey-Doudoroff pathway whose final products are pyruvate and α-glyceraldehyde 3-phosphate (Elshafei & Abdel-Fatah 2001, Khosravi et al. 2015).

The Leloir pathway requires α-D-galactose, but the β-anomer is the most common form released during polysaccharides degradation. Aldose 1-epimerase (EC 5.1.3.3), also known as mutarotase epimerizes β-D-galactose into its α-anomer, which can occur both extracellularly and in the cytosol. α-D-galactose is phosphorylated by the galactokinase (GalK, EC 2.7.1.6) to form α-D-galactose 3-phosphate. Galactose-1-phosphate uridylyltransferase (GalT, EC 2.7.7.12), catalyses the transfer of a UMP group from UDP-glucose to galactose 1-phosphate, generating glucose 1-phosphate and UDP-galactose. To balance the reaction, UDP-galactose is converted to UDP-glucose by UDP-galactose 4-epimerase (EC 5.1.3.2). Finally, phosphoglucomutase (PgmB, EC 5.4.2.2) catalyses the conversion of glucose 1-phosphate into glucose 6-phosphate that enters glycolysis.

GalK (NRRL3_06978) and PgmB (NRRL3_05655) are present in all species while GalT (NRRL3_05970) is only missing in D-mannose Sacce1 Neucr2 Trire2 Talma1_2 Talst1_2 Aspzo1 Pench1 PenchWisc1_1 Aspwe1 Aspcl1 Aspfu1 Neofi1 Aspcam1 Aspnid1 Aspsy1 Aspve1 Aspac1 Aspca3 Aspbr1 Aspni_NRRL3_1 Aspfo1 Asptu1 Absence/Presence

Fig. 8. α-mannose heatmap abundance of A. niger orthologous proteins in the α-mannose catabolic pathway. The legends are the same as that of Fig. 3.

Fig. 9. α-galactose heatmap abundance of A. niger orthologous proteins in the α-galactose catabolic pathways. The legends are the same as that of Fig. 3.
**T. stipitatus.** There are two mutarotases predicted, belonging to different clusters, NRRL3_09251 (intracellular) and NRRL3_05510 (extracellular), which are both present in all species. A second extracellular mutarotase, NRRL3_10372, was found through orthology, and is present in A. wentii, A. clavatus, A. fumigatus and A. niger exclusively. An ancestral group in this cluster contains an N. crassa sequence. Four clusters contain enzymes assigned to UDP-galactose 4-epimerase. GaLE (NRRL3_09025) is the only ortholog present in all species. GaLE and the other members of its cluster (NRRL3_05343 and NRRL3_02929) are the most conserved orthologs assigned to this activity. Phylogenetic analysis showed that almost every species contains one or more orthologs from other clusters, with the maximum number of proteins in section *Nigri*. β-D-galactose is metabolized directly by the oxidoreductive pathway. Several of the enzymes in this pathway have been shown to also be involved in α-arabinose and α-xylene metabolism (Fekete et al. 2004, Mojzita et al. 2010a,b, Mojzita et al. 2012a,b, Metz et al. 2013). The first step is the reduction of β-D-galactose to galactitol (EC 1.1.1.21). The reduction of the galactitol into α-xylene-3-hexulose is catalysed by the galactitol dehydrogenase (LadB, EC 1.1.1.1) followed by reduction to α-sorbitol catalysed by a reductase specific to α-galactose metabolism, the α-xylene-3-hexulose reductase (XhrA, EC 1.1.1.1). Sorbitol dehydrogenase (SdhA, EC 1.1.1.14) catalyses the conversion of sorbitol to keto-D-fructofuranose which through spontaneous reaction is transformed into its furanose form to enter glycolysis after Hxk transfers a phosphate group to it.

LadB (NRRL3_07283) and XhrA (NRRL3_07289) are the only single enzymes assigned in the oxidoreductive pathway, and both appear after *Penicillium* species splits off from the other species. They are missing in *A. clavatus, A. fischeri* and *A. aculeatus*. In contrast, there are several oxidoreductases from the same cluster assigned to the production of galactitol (EC 1.1.1.21), but XyrA (NRRL3_01952) and NRRL3_05038 are the only orthologs present in all species. The last step of the pathway, includes SdhA (NRRL3_04328) and GutB (NRRL3_01929) from two different clusters. GutB is present in all species after *T. reesei* except for *A. campestris*. While SdhA appears after *P. zonata* splits off from the other Eurotiales and is present in all species except *A. clavatus* and *A. campestris*. Neither the *A. niger* NRRL 3 genome functional annotation nor the curated network revealed an aldolase with tagatose-biphosphate affinity suggested in a previous study for the *A. nidulans* genome (Filippelli et al. 2009). This suggests that not all Aspergillli are able to convert α-galactose into dihydroxyacetone phosphate and α-glyceraldehyde 3-phosphate.

In the non-phosphorylated DeLey-Duodoroff pathway, the starting substrate is the β-D-galactose form which is oxidised into its lactone form, α-galactono-1,4-lactone by α-galactose dehydrogenase (EC 1.1.1.48). Gamma 1,4 lactonase (EC 3.1.1.25) converts α-galactone 1,4-lactone into α-galactonate, which is further converted by β-galactonate dehydratase (DgdA and DgdB, EC 4.2.1.6) into 2-dehydro-3-deoxy-α-galactonate. Although no aldolase has been associated to the reaction (EC 4.1.2.51), it has been shown (Elshafei & Abdel-Fatah 2001) that the last reaction produces pyruvate and α-glyceraldehyde from 2-dehydro-3-deoxy-α-galactonate. Pyruvate enters the TCA and glyoxylate cycles while α-glyceraldehyde enters glycolysis as α-glyceraldehyde-3-phosphate after a kinase (EC 2.7.1.28) transfers a phosphate group.

Two enzymes from different clusters have been assigned to α-galactose dehydrogenase. NRRL3_06411 is present in all species, while NRRL3_03123 is missing in *N. crassa, P. zonata, A. clavatus*, section *Fumigati* and *A. nidulans*. A second NRRL3_03123 like group that contains sequences of Talaromyces species, *A. wortii, A. clavati*, section *Fumigati* and some species of sections *Nidulantes* and *Nigri* was found during phylogenetic analysis. A single cluster, contains two γ-1,4-lactonase orthologs (NRRL3_08839 and NRRL3_10750) that are present in most species after Talaromyces, but Penicillium species lack both. Either DgdA or DgdB (NRRL3_08012 and NRRL3_10522) is present in all genomes after *T. reesei*, except in *P. zonata* and *A. nidulans*. An *A. nidulans* ortholog is present in a NRRL3_10522_like (NRRL3_08012_like group as well in other species before *A. campestris*). α-glyceraldehyde 3-phosphate (NRRL3_01127) is detected in all species except *P. rubens*.

For most of the species that were able to grow on α-galactose, mycelia was used as starting material. In spite of the genomes encoding the enzymes needed for α-galactose metabolism, growth from spores is impossible. Different scenarios need to be considered, transportation inside the cell or lack of induction (Fekete et al. 2012). Except for *A. brasiliensis* which was shown to be the only *Nigri* able to grow from spores in α-galactose (Meijer et al. 2011). *A. brasiliensis* protein profile differs from the rest of the section *Nigri* in having a close ortholog NRRL3_05510like. This group further contains *A. versicolor, A. wentii* and both *Penicillium* species orthologs. With the exception of *P. chrysosporum*, all three species show growth on α-galactose from spores. More studies need to be done to understand the different pathways involved on α-galactose metabolism.

**α-galacturonic acid and l-rhamnose metabolism**

α-galacturonic acid and l-rhamnose are both components from pectin and are metabolized through similar but different non-phosphorylated pathways (Alazi et al. 2017, Khosravi et al. 2017). Their recent identification explains why these pathways were not included in the previous inventory of central carbon metabolism in several Aspergilli (Filippelli et al. 2009).

Pectin hydrolysis released α-galacturonic acid monomers that are metabolized through the α-galacturonic pathway (Fig. 10). α-galacturonic acid reductase (GaaA, EC 1.1.1365/1.1.1.1-) converts α-galacturonic acid into aldehyde-l-galactonate. (Alazi et al. 2017), then is converted by GaaB (NRRL3_06890, EC 4.2.1.146), encoding a l-galactonate dehydratase, into 2-dehydro-3-deoxy-l-galactonate. 2-keto-3-deoxy-l-galactonate aldolase (GaaC, EC 4.1.2.54) catalyzes the reaction splitting 2-keto-3-deoxy-l-galactonate into l-glyceraldehyde and pyruvate. Pyruvate enters TCA and glyoxylate cycles among other pathways, while l-glyceraldehyde is reduced to glycerol by aldolase reductase, (GaaDLarA, 1.1.1.372). This enzyme has been shown to also be involved in l-arabitol, d-xylitol, d-eritritol and glycerol metabolism (de Groot et al. 2005, Mojzita et al. 2010a, Jovanovic et al. 2013).

All characterised enzymes, GaaA (NRRL3_05650), GaaB (NRRL3_06890), GaaC (NRRL3_05649) and GaaDLarA (NRRL3_10050) are present in all studied species. A second enzyme (NRRL3_06930) assigned to α-galacturonic reductase activity that belongs to a different cluster than GaaA was found in all species, including *S. cerevisiae*. This enzyme could be the responsible for supporting reduced growth observed on α-galacturonic acid when gasA was deleted (Alazi et al. 2017). Several species contain representatives of two NRRL3_06930 like groups. Another group was found in the
Fig. 10. α-galacturonic and glycerol heatmap abundance of A. niger orthologous proteins in the α-galacturonic and glycerol catabolic pathways. The legends are the same as that of Fig. 3.

GaaB cluster (NRRL3_06890_like) containing sequences from Trichoderma reesei, Talaromyces stipitatus and Penicillium species.

When evaluating growth on α-galacturonic acid, we need to take into consideration glycerol metabolism. Glycerol can be used as carbon source when present in the medium or as an intermediate of other pathways. Glycerol can be converted into sn-glycerol 3-phosphate by the glycerol kinase (EC 2.7.1.30). The reverse reaction is catalysed by glycerol 1-phosphatases (EC 3.1.3.21). Sn-glycerol 3-phosphate is converted into dihydroxyacetone phosphate that enters glycolysis, by two different reversible reactions. A flavin-dependent glycerol 3-phosphate dehydrogenase (EC 1.1.5.3) present in the mitochondrial membrane and a glycerol 3-phosphate dehydrogenases (EC 1.1.1.8). Dihydroxyacetone phosphate can be produced from dihydroxyacetone by a reversible reaction catalysed by glycerone kinase (EC 2.7.1.29). Dihydroxyacetone is produce by the reduction of glycerol catalysed by glycerol hydrogenase (GldB, EC1.1.1.156).

Glycerol 1-phosphatase NRRL3_10933, flavin-dependent glycerol 3-phosphate dehydrogenase NRRL3_10724 and GldB (NRRL3_01127) are present in all species. Glycerol kinase NRRL3_07842 is also present in all species except S. cerevisiae and T. reesei, and its ortholog group NRRL3_07842_like is only missing in section Nigri and N. crassa. Besides NRRL3_10933, another phosphatase has been found in the same cluster (NRRL3_11685), which is only present in some species from section Nigri. The A. wentii genome lacks all glycerol 3-phosphatase candidates (NRRL3_02122 and NRRL3_04170), while the rest of the genomes contain at least one of the orthologs. Glycerol metabolism in S. cerevisiae is an important source of energy, and its genomes contains at least one copy of each enzyme.

With the exception of P. rubens, A. clavatus, A. campestris and A. versicolor, all species are able to grow on α-galacturonic acid as sole carbon source with no difference related to genome content. Therefore, we can assume, that glycerol metabolism is also functional in the rest of the species.

L-rhamnose is released from polysaccharides such as pectin or rhamnogalacturonan type I in its β-pyranose form. Similar to α-galacturonic acid, L-rhamnose is transformed into the furanose form through a spontaneous reaction to enter the L-rhamnose degradation pathway (Fig. 11). L-rhamnose is converted into L-rhamnose-1,4-lactone by a NADH-dependent L-rhamnose-1-
dehydroshomonic (LraA, EC 1.1.1.173) (Khosravi et al. 2017). The
L-rihomonic acid lactonase (LraB, EC 3.1.1.65), catalyses the
hydrolysis of L-rihomono-1,4-lactone to L-rihomonate, while L-
rihomonate dehydratase (LraC, EC 4.1.2.53) converts this into
2-dehydro-3-deoxy-L-rihomonate. The enzyme catalysing the
last step in the pathway, an aldolase (EC 4.2.1.53) remains to be
discovered.

All species contain one copy of each known Lra enzyme, LraA
(NRRL3_01494), LraB (NRRL3_01483) and LraC (NRRL3_01495),
except A. carbonarius that contain more than one copy of all three. A
second paralog of LraA, NRRL3_08837 was found in the same
cluster and is present in all species after P. zonata except A. clavatus, A. campesiris, A. aculeatus and section Fumigati.

A similar phenotype was observed in species belonging to
different clades. Those species that grow on L-rihamone show
either reduced or similar growth to D-glucose, except N. crassa
which shows better growth than on ω-glucose. Interestingly, A.
carbonarius was not able to grow on L-rihamone even though
it has extra copies of all known Lra genes.

Pentose catabolism

Pentose catabolism in A. niger mainly involves two pathways, the
pentose catabolic and pentose phosphate pathways. The
pentose catabolic pathway includes L-arabinose and D-xylulose
catabolism to produce D-xylulose, and the pentose phosphate
pathway includes ω-ribulose, D-ribose and D-xylulose catabolism
and the production of several glycolytic intermediates including
NADPH necessary during glycolysis (Fig. 12).

In the first step in L-arabinose metabolism, L-arabinose
reductase converts L-arabinose into L-riarabitol (GaaD/LarA, EC
1.1.1.-, 1.1.1.21) (de Groot et al. 2005, Mojzita et al. 2010a, Jovanovic et al. 2013). L-riarabitol oxidation to L-xylulose is cat-
alysed by L-riarabitol 4-dehydrogenase (LadA, EC 1.1.1.12) (Kim et al. 2010, Mojzita et al. 2012b). The last step is the reduction of
L-xylulose to produce xylitol by xylitol dehydrogenase (LxrA, EC
1.1.1.10).

D-xylulose conversion into xylitol is catalyzed by D-xylulose
reductase (XyrA, EC 1.1.1.21). The final product of the separate
L-arabinose and D-xylulose pathways, xylitol, is reduced to D-
ribulose by xylitol dehydrogenase (EC 1.1.1.9), which is phos-
phorylated by D-xylulose kinase to form D-xylulose 5-phosphate
(XkA, 2.7.1.17).

D-xylulose 5-phosphate originates from the pentose catabolic
pathway and is one of the main substrates of the pentose
phosphate pathway. Glycolysis connects to the pentose phos-
phate pathway through D-glucose 6-phosphate conversion to 6-
phospho-D-glucolate-1,5-lactone by the glucose-6-phosphate 1-
dehydrogenase (GsdA, EC 1.1.1.49) (van den Broek et al. 1995). 6-
phosphogluconolactonase (EC 3.1.1.31) hydrolyzes 6-
phospho-D-glucono-1,5-lactone to produce D-glucurate 6-
dehydrogenase, which is further catalyzed by 6-phosphogluconate
dehydrogenase (EC 1.1.1.44) to D-ribulose 5-phosphate. The D-
ribulinate pathway also connects to the pentose phosphate
pathway through D-glucurate 6-phosphate.

D-ribulose 5-phosphate can be produced from the degrada-
tion of D-ribulose catalysed by ribulokinase (RbtA, EC 2.7.1.47),
and is then converted by ribulose-phosphate 3-epimerase
(RpeA, EC 5.1.3.1) to D-xylulose 5-phosphate or by ribose 5-
phosphate isomerase (Rpi, EC 5.3.1.6) to D-ribose 5-
phosphate. Transketolase (TktA, EC 2.2.1.1) catalyses the re-
action between D-ribose 5-phosphate and D-xylulose 5-phosphate
to produce D-sedoheptulose 7-phosphate and D-glyceraldehyde
3-phosphate. The latter can enter glycolysis or be utilized by transaldolases (Tel, EC 2.2.1.2) to produce α-erythrose 4-
phosphate and β-fructosefruano 6-phosphate that can also
enter glycolysis or other pathways. Transketolase (TktA), can
also convert α-erythrose 4-phosphate and D-xylulose 5-phosphate
into β-fructose 6-phosphate and D-glyceraldehyde creating a
loop in the pathway. A different transketolase (TktB, EC 2.2.1.3)
catalyses the production of D-glyceraldehyde and dihydroxyac-
etone from D-xylulose 5-phosphate and formaldehyde.

Except for XkA (NRRL3_04471) that is present in all species,
all reactions in the pentose catabolic pathway have multiple en-
zymes assigned. Five enzymes have been assigned to L-arabitol
and xylitol production. Through phylogenetic analysis, we found
a total of eight proteins predicted to be involved in those reactions,
but only two have been biochemically characterised GaaD/LarA
and XyrA (Hasper et al. 2000, Jovanovic et al. 2013). In vitro
analysis showed activity of GaaD/LarA and XyrA on L-arabinose, D-
xylulose and for the latter on D-galactose as well, but growth on L-
arabinose or D-xylulose is already reduced when LarA or XyrA are
missing (Mojzita et al. 2010a). GaaDLarA (NRRL3_10050) shows
the highest affinity for L-arabinose and L-arabitol while XyrA
(NRRL3_01952) shows higher affinity for D-xylulose and xylitol
compared to other enzymes. Orthologs of both genes can be found
in all studied species. TheNRRL3_05038 ortholog is also found in
all species. Interestingly, both XyrA and NRRL3_05038 are the
only enzymes for these reactions that are also present in S. cerevisiae
and N. crassa. The other genomes contain different orthologs for
different enzymes, up to eight in some species from section Nigri. LarA (NRRL3_02523) is present in all species but its
ortholog NRRL3_00896 is missing in N. crassa, T. stiptatus, P.
zonata, A. clavatus and A. campesiris. Those species together
with Trichoderma reesei, Talaromyces marneffei, Penicillium
species, A. campesiris and sections Fumigati and Nidulantes also
miss NRRL3_08407 in their genome. LxrA (NRRL3_10884) is the
only xylitol dehydrogenase characterised and it is present in all
species. From the same cluster, NRRL3_04510 is missing in the
genome of A. campesiris. Species from section Nidulantes contain
all four orthologs.

Several enzymes have been assigned to D-xylulose production
but only some of them have been biochemically characterised.
XdhA (NRRL3_09204) shows the highest activity with xylitol and D-
xylulose, while LadA (NRRL3_02523) is also active on xylitol and
D-xylulose but has higher activity on L-arabitol and D-xylulose (de
Groot et al. 2007). XdhA, LadA and NRRL3_00319 are present
in all species. From the same cluster, five additional orthologous
groups were identified. A. wentii, A. versicolor, A. brasiliensis and
A. niger contain representatives of all eight groups.

GsdA (NRRL3_05283), RbtA (NRRL3_00588), RpeA
(NRRL3_00279), RpiA (NRRL3_10107) and TktA (NRRL3_11249)
are present in all species, while PgiA (NRRL3_02043) is missing in A. campesiris. Two different clusters contain five enzymes with 6-
phosphogluconate dehydrogenase activity (EC 1.1.1.44), which
were found through phylogenetic analysis. Only NRRL3_09981
is present in all species, including S. cerevisiae. Most of the species
contain also NRRL3_09641 and NRRL3_09981 orthologs, except
for T. reesei, but NRRL3_08784 is only present in A. wentii, A.
sydowi, A. versicolor, A. aculeatus and A. niger.

Ribose 5-phosphate isomerase assigned enzymes (RpiA:
NRRL3_10107 and RpiB: NRRL3_06024) belong to different
clusters. RpiB is missing in A. fumigatus, while
NRRL3_06024_like group only contains orthologs from A. wentii.
and A. campestris. There are two transaldolases predicted (TalA, NRRL3_04528 and TalB, NRRL3_04473) that belong to the same cluster. TalA is missing in A. fumigatus while TalB is missing in T. reesei, A. clavatus, A. fumigatus and some species from section Nidulantes. This implies that there is no transaldolase similar to these genes in A. fumigatus, which implies that a non-homologous gene is responsible for this function or that the gene has not been identified or assembled in the A. fumigatus genome. In contrast, NRRL3_04473 like orthologs are only present in A. aculeatus, A. carbonarius, section Nidulantes and Penicillium species. Dihydroxyacetone synthase (EC 2.2.1.1), TktC (NRRL3_00895) and NRRL3_10165 belong to the same cluster as TktA (NRRL3_11249, EC 2.2.1.1). They have been assigned a different reaction in the network. They catalysed the production of dihydroxyacetone and D-glyceraldehyde 3-phosphate from D-xylulose 5-phosphate and formaldehyde. Only Penicillium species, A. versicolor and A. luchuensis contain all three orthologs predicted, most species contain only two orthologs in their genomes.

All species were able to grow on l-arabinose and D-xylose to different degrees. Interestingly, even though both *Penicillium* species have the same pattern (except extra copies of NRRL3_09641) they behaved differently. *P. chrysogenum* grew on D-xylose as good as on D-glucose while *P. rubens* showed better growth on l-arabinose but always lower than on D-glucose. *A. campestris* grew better than any other species on l-arabinose compared to D-glucose, despite missing several orthologous enzymes for most of the activities. Yeasts like S. cerevisiae are known for being unable to grow on pentoses unless genetically modified (Jeffries 2006, Hahn-Hagerdal et al. 2007). As shown in the Fig. 12, they miss most of the orthologous proteins involved exclusively in pentose catabolic metabolism, but not pentose phosphate metabolism that is needed to produce NADPH for glycolysis.

**DISCUSSION**

Automated pipelines for genome assembly, gene prediction and functional annotation have evolved over the years to handle increasingly larger next generation sequencing output files. At the same time, human supervision has reduced compared to the initial genomes. In our protein assessment analysis, we show...
how gene prediction quality varies between genomes regardless of organism, technology or consortia. Comparing the predicted proteome against a database of conserved proteins enables evaluation of the completeness of the proteome and therefore the quality of the gene annotation and genome assembly. Different options can be used to improve a new genome. The most common option is to use a similar genome from a closely related species to improve gene prediction and functional annotation, but this only provides significant improvement if that genome is of high quality. However, not many high-quality genomes are available. Gold-standard genomes are difficult to acquire, they require a high amount of omics data and manual curation by experts at every stage of the process. We showed in this study that more than 90% of predicted proteins in genus Penicillium shared sequence similarity with proteins from genus Aspergillus. Using a gold-standard genome can improve gene prediction and protein functional annotation and, if combined with metabolic network analysis, it can be used to predict metabolic pathways with higher confidence. This analysis goes significantly beyond the use of the KEGG automatic pipeline together with orthology analysis and a partially completed genome sequence that was used in the previous study based on A. nidulans (Flipphi et al. 2009).

In this study, we also showed how orthology and protein profiling based on a manually curated metabolic network of a gold-standard genome (A. niger NRRL 3) can be used to predict primary carbon metabolism in a number of species and correlate the genome content with growth abilities. As expected, more distant Ascomycota, S. cerevisiae, N. crassa, and T. reesei, contain lower number of orthologs of A. niger NRRL 3 genes compared to other members of the genus Aspergillus. In particular, S. cerevisiae lacks several proteins and even complete pathways compare to A. niger NRRL 3.

Glycolysis operates with remarkable efficiency if we consider the number of pathways that link to glycolysis through d-glucose 6-phosphate and d-fructose 6-phosphate. Some of the steps of the pathway have been associated with several enzymes, but we find less redundancy in key enzymatic reactions, especially in the steps leading to production of pyruvate from d-glyceraldehyde 3-phosphate. Species from section Nigri are known for citric acid production (Max et al., 2010), which correlates with the high number of orthologous genes assigned to the glyoxylate and TCA cycles. A similar pattern is observed for the genes involved in d-glucuronate production from d-glucose, which also correlates with previous data showing that Penicillium and Aspergillus section Nigri species are high gluconate producers (de Vries et al. 2017).

A clear example of the presence of an alternative pathway is growth of S. cerevisiae on d-glucuronate (Oliva Neto et al. 2014), while our study indicates that its genome misses all the enzymes of the pathway. Another example of alternative mechanism occurs during growth on sucrose. S. cerevisiae, N. crassa, P. zonata, A. clavatus, and A. campestris genomes lack all three GH32 proteins identified in A. niger, even though they can grow on sucrose almost as well as on d-glucose and d-fructose. This suggests that these species contain a non-homologous alternative enzyme that can split sucrose.

In contrast, the A. clavatus genome contains genes that encode for all identified enzymes necessary for d-galacturonic catabolism, but it is not able to grow on d-galacturonic acid as a sole carbon source. A possible explanation for this is the absence of the galacturonic acid transporter in A. clavatus (Mäkelä et al. 2018). Tight regulation on the transporter seems to be causing the lack of growth from spores on d-galactose as sole carbon source (Fekete et al. 2012). Even though most species contain orthologs for the A. niger genes, most of them are still unable to grow from spores, similar to what is observed for A. niger itself. They are able to grow when small amounts of other monosaccharides are present in the media or when they are inoculated from mycelia, which supports that the problem is mainly related to uptake of d-galactose during germination.

In summary, we show that combining a gold-standard genome with a manual curated metabolic network and phylogeny can significantly improve functional annotation of less studied species. It helps with the identification of essential proteins and alternative pathways for the degradation of several compounds that otherwise could have been missed or required significant efforts through classical genetics. We observed low diversity between closely related species for monosaccharide catabolism, and even high conservation between more distant fungi. This is likely due to the important role monosaccharides have as a carbon source for fungi. We can expect a higher diversity between species for other aspects of fungal biology, such as in polysaccharide degradation, transport affinity and regulatory systems. In fact, other papers in this issue reveal high diversity with respect to plant biomass degradation (Mäkelä et al. 2018), stress tolerance (Emri et al. 2018) and sexual and asexual reproduction (Ojeda-López et al. 2018).

ACKNOWLEDGEMENTS

The authors would like to thank Jos Houbraken for his help with fungal taxonomy. This work was carried out on the Dutch national e-infrastructure with the support of SURF Cooperative Grant e-infra 170088, and on funding from Genome Canada and Génome Québec. M.V.A.P. was supported by a grant of the Dutch Technology Foundation STW, Applied Science division of NWO, and the Technology Program of the Dutch Ministry of Economic Affairs 016.130.609 to R.P.dV.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1016/j.simyco.2018.10.001.

REFERENCES


