

COMPARATIVE ANALYSIS OF GENE FINDING TOOLS WHEN
APPLIED TO *Trichoderma* GENOMES

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Abstract

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List of Abbreviations

DNA	Deoxyribonucleic acid
RNA	Ribonucleic acid
CDS	Coding sequence
Mb	Megabases
Kb	Kilobase
WGS	Whole Genome Shotgun (sequencing)
NGS	Next generation sequencing
PCR	Polymerase chain reaction
GMO	Genetically modified organism
CPU	Central processing unit
GC	Guanine cytosine
HMM	Hidden Markov model
UTR	Untranslated region
GFF	General feature format
BUSCO	Benchmarking Universal Single-Copy Orthologs
RSMI	Root, Soil and Microbial Interactions
MITE	Minature inverted-repeat transposable element
TIR	Terminal inverted repeat
TDR	Terminal direct repeat
maybe	Should I include tools like BLAST and resources like NCBI?

1 Introduction

The study of organisms in Biology is a highly complex process involving many disciplines. To better understand how these organisms function, we must break down the problem into different sub-problems. One important sub-problem in biology is the understanding of the molecular tools and processes used by cells to function in normal and abnormal environmental scenarios or stress conditions. These conditions may include disease and environmental stress for example. However, previous work in biology has shown that the underlying backbone of information, known as the genome, can vary widely between different organisms in many aspects, such as overall structure, length, ploidy, methylation, and overall gene content. All of these aspects can affect the survival of an organism in any given environment, some of which may be interesting to researchers. As an example, one of the most popular and extensively studied diseases is cancer. Through the study of human genomes, researchers identified a key gene, named TP53, involved in the suppression of tumours. Functional mutations affecting this gene can result in increased risk of cancer. Understanding how and why TP53 suppresses tumours can provide insight into future cancer prevention methods and treatments. These genes can then be mapped to the genome of the organism to identify its location.

This general workflow can be applied to features of interest from organisms in all branches of life. To facilitate this process of identifying genes from a genome, the process of genome annotation was developed. In this case, instead of identifying a gene of interest and then mapping it back to the genome, gene finders identify potential genes from a reference genome before truly knowing their function or if the candidate is truly utilized by the organisms. This set of potential genes acts as a reference for future research. However, to generate a reliable set of possible genes, a gene finder must be supplied with a suitable high quality genome. In many cases, researchers may be studying a specific strain or variety of organism that differs from the reference assembly and annotation available for the organism of interest. Rather than using the reference assembly for analysis, it may be beneficial to generate a new assembly for the unique variety or strain, which must then be passed through a gene finding tool. With the variety of gene finding tools and approaches, the choice of an appropriate tool can affect the resulting gene set. This problem raises a question. Do the results from gene finding tools differ? And more importantly, how should one compare results from gene finding tools when there is no reference annotation for a specific variety in question? Most genome annotation tools benchmark their performance in comparison to an existing reference annotation, which is usually considered to be of suitably high quality. This is not possible in the case of unique assemblies, and so the development of a comparative methodology is in order.

2 Background

2.1 Genomics

Genomics is a wide area of study focusing on the genomes of organisms from all varieties of life. A genome is a sequence of characters that contains the fundamental set of 'rules' used to create what we know as life. One can think of a genome as a set of instructions that our cells use in order to complete the tasks that make us function. A genome is comprised of tightly bundled sequences of DNA, which are stored in the nucleus of cells. These bundles of DNA contain sections known as genes, which can be thought of as the tools described by the set of instructions. These tools carry out a vast number of processes ranging from no known function at all to genes that are key in protecting against diseases cancer. Genomes can vary widely in size, ranging from small bacterial genomes of roughly 4 Mb up to approximately 149000 Mb. Piecing together genomes provides numerous opportunities to understand other 'omics' within cells, such as proteomics, metabolomics, transcriptomics and epigenomics.

2.1.1 Sequencing

Sequencing data is a pivotal form of data used in nearly all applications of Bioinformatics. To understand the processes used by organisms for day to day survival or in unique circumstances, we must have an initial set of data points to work with. These sequences, referred to as reads after sequencing, are the foundation for solving problems ranging from taxonomical classification to the understanding of complex biological functions like signaling pathways. Reads may come in a variety of forms and formats depending on the desired application.

2.2 Whole Genome Shotgun Sequencing

Whole Genome Shotgun sequencing (WGS), is a method to produce a large number of genomic sequences from a sample of interest. This form of sequencing is quite common as it has a wide variety of applications in research [1]. WGS involves slicing up genomic DNA into smaller segments. These small segments are then processed further resulting in a set of physical molecules that can be supplied to a compatible sequencing platform of which there are a variety. Modern sequencing platforms are comprised of next generation sequencing (NGS) and 3rd generation sequencing approaches.

2.3 Next Generation Sequencing - Illumina

Illumina sequencing is one of the most popular NGS platforms currently available. Illumina sequencing produces a very large number of high quality short reads, typically between 75 and 250 base pairs in length. Sequencing libraries can be prepared to produce reads solely from one end of a sequence fragment (single-end) or both ends (paired-end). Advantages of paired end sequences are the additional context provided by the paired sequence on the opposite end of the fragment. This context is leveraged by read processing tools to identify features such as repetitive regions and genomic rearrangements, which can be significant in downstream analyses. Illumina sequence libraries are generated by first fragmenting the DNA samples, amplifying them via PCR, ligating adapters that allow the sequence to bind to the sequencing plate, and finally identifying each fragment's sequence of nucleotides using fluorescently-labeled nucleotides that bind to the fragments [5].

2.4 3rd Generation Sequencing - Nanopore

Nanopore sequencing data is relatively recent approach to sequencing projects. While Illumina reads are considered to be short, Nanopore reads are much larger, ranging from 10Kb to 300Kb depending on the approach used. Long reads are beneficial due to their ability to bridge the gaps between difficult to assemble regions when performing sequence assembly. An example of a difficult to assemble region would be a region with a high repeat content, where a large number of small repeats may be collapsed during the assembly process, resulting in an assembly that does not represent the true nature of the sequence being studied [9]. While Nanopore was previously known for having lower quality base calls when compared to Illumina, that is no longer the case at this time. Nanopore sequencing works by passing long segments of genetic sequence through a membrane bound protein and measuring changes in electrical current, which is characteristic of the nucleotide at a given position.

2.5 Trichoderma

Crop resistance to environmental stressors is a necessity for crop health and overall crop yields. Current popular methods for crop protection involve the use of pesticides and genetically modified organisms, which can be expensive and potentially politically dividing in the case of GMOs[15]. In addition, crops suffer when soils are not sufficient for crop growth and health. Soil insufficiencies can result in drought stress as well as nutrient stress, leading to poor overall yields.

Trichoderma is a fungi that can both communicate with and colonize the roots of plants in a non-toxic, non-lethal, opportunistic symbiotic relationship[18]. Many strains of *Trichoderma* have been shown to provide resistance to pathogenic bacteria and other fungi in soils through the use of polyketides, non-ribosomal peptide

synthetases and other antibiotic products[18]. Recently, two strains of *Trichoderma* have been identified in the prairie regions of Alberta and Saskatchewan. These two strains, named Tsth20 and DC1, have been found to have beneficial properties when used as an inoculant for plants in the soils mentioned before. In addition to these beneficial properties, the two strains mentioned previously provide even further protection for plants in dry, salty soils and one strain also has potential for use as a bioremediation tool in soils contaminated with hydrocarbon content. Bioremediation and resistance to drought tolerance has also been investigated in other strains of *Trichoderma* as well[13]. However, little is known about the mechanisms at work in these strains, so DC1 and Tsth20 were sequenced by the Global Institute for Food Security (no publication yet) in an initial attempt to better understand the details of these genomes. While this research does not directly identify genomic elements related to the secretome of these genomes, it may serve as a foundation for future research of *Trichoderma*.

2.6 Genome Assembly

Sequence assembly has been a long-standing problem in the field of bioinformatics[10]. Determining the correct order and combination of smaller subsequences into an accurate complete sequence assembly is computationally difficult in terms of compute resources such as memory, CPU cycles and storage required for input sequences[10]. In addition to these difficulties, there can be other issues encountered during assembly due to the nature of the data or genomes themselves, such as low quality base calls for long read data, which is not necessarily the case today, or the inherent content of genomes themselves using repetitive regions as an example. Insufficient data used in an assembly may result in short, fragmented assemblies, depending on the size of the genomes, while sequence data that is not long enough can fail to fully capture repetitive regions in an assembly. To solve this problem, a wide range of assembly tools have been developed with their own unique approaches to the genome assembly problem, so it is important to use an appropriate assembler for the task at hand, and also important to evaluate the assembly thoroughly.

Genome assembly tools generally approach the assembly problem using a graph-based approach. The most common graph-based approach is the de Bruijn graph assembly [3]. A graph in this context, is set of nodes (k -mers from sequences) connected by edges (overlaps between k -mers). Traversing through this graph results in longer subsequences that ultimately result in a set of consensus sequences and final assembly. In the early years of long read sequence data, sequencing platforms encountered difficulties producing consistently high scores for base calls when sequencing. To combat this, some assembly workflows may also include a polishing or correction step once the initial assembly is completed in which high quality short read sequences are supplied as supplemental information to correct low quality base calls in the assembly. These low quality base calls are typically not present in modern long read sequencing approaches as the methodology and quality of calls have improved drastically. While the polishing step is arguably unnecessary in modern assemblies, the polishing programs remain available should researchers be interested in applying additional reads for

polishing.

One approach to aid in the previously mentioned issue of assembly correctness is to use a combination of long and short reads in what is known as a hybrid assembly. Combining both highly accurate short reads with deep coverage along with less accurate but much longer reads can produce high quality genome assemblies that capture long repetitive regions. Hybrid assembly approaches have been shown to produce high quality assemblies in a wide variety of organisms as they combine long read data with short data to produce assemblies that properly represent long repetitive regions with additionally high quality Illumina sequences for correction. Once assembled, the sequences must also be evaluated with measures such as N50, L50, coverage, average contig length and total assembled length to ensure that the genomes are well assembled, at least based on these metrics[10]. Following appropriate assembly protocols is essential to the further success of a project as downstream processing such as annotation depends on a high-quality assembly.

2.7 Identification of AT-rich Genomic regions

One important aspect of interest when assembling any form of sequence is GC content or percent GC of the assembled sequence. Large regions of anomalous GC content may be of interest to researchers as they may contain repetitive regions and unique features responsible for traits specific to the organism in question.

2.8 Repeat Identification and Masking

Repeat identification within assembled genomes is a problem that needs to be considered during the genome annotation process. Regions with long repeats can have a significant impact on genome assembly as well as gene finding due to the limitation of short reads used in some assemblies[16]. Short reads may be unable to bridge or cover entire repeat regions within a genome, so it is important to consider the use of long reads from technologies such as Nanopore or PacBio to provide a complete picture of these regions when pursuing a new genome assembly project. It is also possible for repetitive regions to contain genes as well, making for an interesting investigation in regards to *Trichoderma*, as fungal genomes have been shown to contain many repeat regions with a high concentration of A and T nucleotides[17]. Once these repetitive regions have been identified, the genome could be masked to exclude these regions in downstream processing if desired, as these regions may be poorly assembled and may result in found genes that do not truly exist in those regions. However, this may not be as common today, as repetitive regions have been shown to contain genes as well[14]. This may affect the gene finding process described later and may be an interesting topic to look into considering the large number of available gene finding programs.

2.9 Centromere Identification

A centromere is a region of a chromosome that is crucial for the proper cell division. These regions are the main anchor for microtubules, which are a cellular structures used that attach to centromeres to separate chromosomes during both mitosis and meiosis. Centromeres are critical to the survival of an organism, with malfunctions in the process of cell division usually resulting in potential disease and fatal outcomes[12]. Centromeric sequences can be comprised of several different genetic components, with repetitive regions being the most prevalent in the forms of satellite DNA and transposable elements. In addition to centromeric regions, there are flanking pericentric regions with their own properties, including potential candidates for small-interfering RNAs[12]. Identification and consideration of centromeric regions may prove useful when comparing the outputs of gene finding tools, as the underlying properties and structure of the genetic sequence differ in comparison to typical coding regions of DNA.

2.10 Gene Finding Methods

Gene finding (or gene annotation) has been a long standing computational problem in bioinformatics, which concerns itself with identifying potential genes within assemblies based on patterns or pre-existing experimental evidence considered by the gene finding program. This process is critical for unraveling and understanding the complex processes occurring in all forms of life with applications in medical science, agriculture, biomanufacturing, environmental studies and many others. In a general sense, gene finding programs operate by searching for patterns or indicators showing that a gene of feature may be present. The most basic indicators being start and stop codons, with introns and exons in between should the sequence match the applied model. The results produced by gene finding tools can vary considerably for a number of reasons, including quality of the assembly, the intrinsic model used by the gene finder, filtering criteria, and even the nature of the organism and assembly itself. Given the broad applications, choice of gene finding tools, and the variability of assemblies being considered, it is important that we gain a deeper understanding of these tools prior to putting them to use.

There are two common methods for gene finding, those methods being *ab initio* methods, where programs search for patterns and gene structures, and similarity or evidence-based searches, which use prior information such as RNAseq data, expressed sequence tags and expressed protein sequences to identify genes within a new genome[4]. Complicating the process more is the introduction of introns and alternative splicing in eukaryotes, making it possible for one gene to have several possible transcripts at the same locus. An example of an *ab initio* method would be GeneMark-ES[7], while an evidence based tool would be Braker2[2]. *Ab initio* gene finders typically predict genes using a Hidden Markov Model (HMM)[4]. These predictions are based on 'signals' or features associated with a gene, such as the usual start, stop, exon and intron portions of a gene as well as upstream promoter sequences and more. In this case, these signals would be considered states

in the terminology associated with HMMs. Gene finders wish to predict these states based on observations, or sequences presented to the model. HMMs in gene finding tools are trained beforehand and then applied to a sequence. This means that a gene finding program may not be trained in the context of any assembly provided to it, and thus may miss genes that are unique to the assembly in question. On the other hand, while still relying on HMMs for a 'base' set of predictions, evidence-based gene finding tools leverage new evidence that may be outside the scope of the pre-existing model[?]. As an example, an evidence-based model would be useful in a situation where you are interested in annotating a new assembly for a non-model organism. The addition of experimental data provides context specific to your assembly of interest while still retaining the predictions from existing HMM models.

There are also other aspects of gene finding tools that are important to consider. These include features such as whether or not the gene finders find non-coding RNAs, annotation of 5' and 3' UTR regions, and in the case of ab-initio methods, the assumptions made by the underlying models used for gene finding. These features and others can influence a user's decision on which gene finding tool to consider and will complicate comparative analysis of multiple gene finding tools. (citation needed somewhere in here)

2.11 InterProScan

The outputs from gene finding tools are a set of potential genes that fit the model used by each tool. While they are considered genes, the use of the word gene is used in a very loose sense, in that these genes may or may not be functional or match any existing gene sequences from previous research. Typically, to confirm the 'correctness' of predicted genes, the outputs from a given tool are used in a sequence similarity search against a reference set of genes or a large database comprised of multiple organisms. This approach is straightforward, but can introduce bias from database choice and also allows for vague or loose matches, depending on the parameters used and the interpretation of the results. Another approach is to use InterProScan, which is a tool used for functional annotation of proteins using evidence from a variety of databases [?]. The presence of some form of functional domain or annotated structure in a predicted gene sequence is reasonable evidence for the existence of a predicted gene. In addition. This approach also avoids the problems associated with similarity-based approaches.

2.12 File Formats

2.12.1 FASTA

One of the most popular formats for sequences of DNA, RNA and amino acids is the FASTA format. The FASTA format consists of one or more entries containing two or more lines. The first line of an entry is the ID line, which must begin with a greater-than ('>') character, followed by an ID and any other pertinent information for the following sequence. The greater-than character is the indicator that a new sequence has


```

>rna1
ATCGTAGTGTGATCGTAGTCGGATTGGACATGATCGATTTCGAT
TGATTGATCGATTGCTAGAAATCGATCGGCTCGTATATCGATCGTA
ATGTCGTTAGTCGAT
>dna2
ATTAGTCGATGCTAGCTGATGGTTAGCTAGTTCGATTCGGTATAGATCTAGGCTTAGAGATATCGCGCTAGCTAGCTAGC

```

Figure 2.1: Example of two FASTA sequence entries. One example with sequence characters split across multiple lines, and one showing all sequence characters on the same line.

```

@M00833:808:000000000-CJYGN:1:2105:15607:1332 1:N:0:1
CAACTGACGTAGGTGGGACATTCTCAACGATGATCCTGCGAGGAATGCGATGGAGGGGCGCAGATGCGGGTTTTGGTTCTAGATG
CCCCGTCAGCGGTTGCGCATGTGGCTTTGCCTTTTTCTTTTTTTTTTTTTGTTTTCTGTTTTTATAGTGTTCGGAACAGC\
CTCTTTTGGACTTTTTTTTTTGGAACTCGCTGCTGGAATGCTGGGTTTTGGTCCCTTTAGGTTTTGGCTTACTGTT
+
AABCBFBBFAAFGFGGGGGGGHHHHHGGFGGHGFHHHHHGGGGGBFGHGGHGEHHGGGGGGGGHHGGGEFGGHGHHHHHHGGH
HHHGHGHHGHHGGCFGGGGGFHHHHHHHHHHHGGHGGHGGHGGGGGFC-;-;BFFE/00:FFF.-D.B000;FBA-.-//:\
9//;BFFF=-;0;FFFFFFFF;-:B9/00.-...0;0.;009000./.9;.-:0F.F00;0:0009.-00:0;00;0

```

Figure 2.2: Example of the four lines in a FASTQ entry.

begun. The following line(s) contain the actual sequenced nucleotides or amino acids, which can be contained on one line or split across many lines. An example of multiple FASTA entries are shown in figure 2.1.

2.12.2 FASTQ

Another popular sequencing format is the FASTQ format. This format is very similar to the FASTA format but with the addition of two more lines per sequence entry and a change to the character indicating the beginning of a new sequence entry. An example of a FASTQ entry is shown in figure 2.2. In FASTQ formatted entries, the greater-than (‘>’) character is swapped with the at (‘@’) character. The IDs for the sequence also follow a specific format, which provide information about the sequencing run and flowcell that the read was sequenced on. This information can then be traced back to the sequencing experiment in the case that there were errors or anomalies in the output from the experiment. Following the ID is the string of base calls. The third line in a FASTQ entry is a plus (‘+’) character, which indicates that the sequences character line has finished. Following the plus (‘+’) character is another sequence of characters, this time indicating the quality of basecall for the corresponding nucleotide base calls in the second line. The quality information included in FASTQ files are used to assess the quality of a sequencing run and extensively used in downstream processing steps, most notably in alignments.

2.12.3 General Feature Format - GFF

General feature format (GFF) is a popular format for storing information about features relative to a position on a genetic sequence, and comprises a large portion of annotation results from this work. These features can be whatever the user desires, as long as the feature entry follows the required GFF guidelines. Relative to a reference sequence, each GFF entry contains the following tab-delimited columns: sequence ID, source, feature type, start position, end position, score, strand, phase, and a semi-colon delimited list of attributes. GFF files are widely supported across bioinformatics tools, making them highly versatile while

```

ctg000000 AUGUSTUS gene 10842 11309 . - . ID=g4;
ctg000000 AUGUSTUS mRNA 10842 11309 0.6 - . ID=g4.t1;Parent=g4;
ctg000000 AUGUSTUS stop_codon 10842 10844 . - 0 ID=g4.t1.stop1;Parent=g4.t1;
ctg000000 AUGUSTUS CDS 10842 11309 0.6 - 0 ID=g4.t1.CDS1;Parent=g4.t1;
ctg000000 AUGUSTUS exon 10842 11309 . - . ID=g4.t1.exon1;Parent=g4.t1;
ctg000000 AUGUSTUS start_codon 11307 11309 . - 0 ID=g4.t1.start1;Parent=g4.t1;

```

Figure 2.3: An example of GFF entries for a single gene.

also remaining relatively simple in nature but also allowing for storage of more complicated items via the attributes column. One significant usage of GFF files is in visualization of features against the reference sequence from which they were derived. Most genome viewers (or browsers) support GFF files as input, allowing intuitive visualization of many features when overlaid on a reference sequence. An example of a GFF entry can be seen in figure 2.3.

Background for BUSCO (from research questions) As more and more genomes are assembled for new organisms, a tool was developed to evaluate assemblies and subsequent annotations from the perspective of gene orthology. As genomes diverge evolutionarily, it is expected that some genes will be conserved. The BUSCO (Benchmarking Universal Single-Copy Orthologs) tool and datasets were developed to assess completeness of an annotation in comparison to evolutionarily conserved genes.

3 Research Questions

3.1 Research Questions

With an ever-increasing number of gene prediction tools available to users, it is important to assess and understand their behaviour and performance in the context, particularly in the context of new genome assemblies of lesser studied organisms, where a reference prediction set may not be available. The main purpose of this research is to evaluate and compare gene finding tools in the context of *Trichoderma* assemblies where a gold standard set of gene predictions does not exist. To assess behaviour and performance in these contexts, we have defined X problems to profile the selected gene finding tools. In addition to applying selected gene finding tools to novel *Trichoderma* isolates, Tsht20 and DC1, we also applied selected gene finding tools to existing *Trichoderma* assemblies from the National Center for Biotechnology Information (NCBI).

3.2 *Trichoderma* Assembly Results

Since gene finding tools operate on an assembled genomic sequence, it must follow that the results will be influenced by the supplied assembly. Before applying gene finders to the new assemblies, we should first investigate the new assemblies by generating general assembly metrics for the new assemblies to contrast and compare with existing assemblies. We ask: **how do assemblies of DC1 and Tsth20 compare to existing *Trichoderma* assemblies?** With these isolates being from the *Trichoderma* family, we expect assembly metrics to be similar in nature to existing assemblies from NCBI, but do they?

3.3 Profiling of Gene Finding Tools

Different gene finding tools may predict different types of features associated with gene structures. The question arises: **which (if any) gene finders predict additional features outside of the standard gene model?** Additional features in this case include promoter sequences, transcription binding sites, activating sequences and other upstream or downstream sequences. In addition, different gene finding tools employ differing programming languages and algorithms which raises several questions. **How are these gene finding tools implemented? Is the software straightforward to install? Are the tools user-friendly? What is the processing time and memory consumption of different gene finding**

tools in the context of *Trichoderma*?

3.4 Number of Features Predicted

Do gene finders predict similar numbers of features in the context of *Trichoderma* genomes?

One common method for evaluating gene finding tools is by looking at the number of features predicted by each tool. These features make an obvious point of comparison for selected gene finding tools. The term ‘feature’ here is somewhat ambiguous, referring to many possible categories of genomic feature. For each gene finding tool, we compare the counts for predicted genes, transcripts, and coding sequences.

3.5 Lengths of Predicted Genes

Genome assemblies can contain a wide range of gene lengths. For some users, genes of a specific length may be a key point of interest, so the ability of a gene prediction tool to capture the broad range of possible gene lengths is another important metric for comparison. Thus we ask the question: **do different gene finders predict genes of similar lengths in *Trichoderma*?**

3.6 Performance in Regions of Anomalous Sequence Content

One of the inspirations for this research is the unique composition of genomic sequence in *Trichoderma*. Results from the assembly process show that GC content in *Trichoderma* strains is abnormal throughout most assemblies. These regions of assemblies present an interesting opportunity to assess gene finding performance in regions of anomalous GC content. The question follows: **do gene finders behave differently in regions of anomalous sequence content?**

3.7 BUSCO Completeness

The use of existing benchmarks for gene finding performance is useful when assessing performance of gene finding tools, particularly in the case of genes that should be evolutionarily conserved. **Do gene finders predict conserved single-copy orthologs expected in fungal genomes?**

3.8 Identifying Regions of Agreement and Disagreement

With predicted genes from several tools available, the question we would like to ask is whether or not the gene finders agree with one another for any given prediction. To answer this question, we will identify ‘regions’ of overlapping predictions. A region can be defined as a start and stop position of a set of individual or overlapping features from one or more gene finding tools and external sources. With regions identified,

we can determine agreement, or more importantly, disagreement in predictions between gene finding tools from which we can ask: **do gene finders agree on their predictions? If no, to what extent do they disagree? Are there genomic regions where agreement or disagreement are more prevalent?**

3.9 Validation of Predicted Genes via InterProScan

In an effort to validate, or at least provide supporting evidence for any given gene prediction we will apply InterProScan to coding sequences predicted by each of the gene finders to identify features associated with protein function. Genes will be considered as ‘valid’ if the gene’s protein sequence contains binding sites, motifs, or other functional characteristics of proteins. Using the results from InterProScan, we ask the question: **in the context of *Trichoderma*, do proteins predicted by gene finders contain functional signatures?**

3.10 Identification of a Core *Trichoderma* Gene Set.

Using results from identification of regions in section 3.8 we will identify a shared or ‘consensus’ set of predictions for each *Trichoderma* assembly. **Can we identify a set of consensus predictions from gene finding results? What are the properties of the resulting set?**

3.11 Selection of a Gene Finding Tool

With all the results generated, we can provide insight to the question: **which gene finding tool should one choose?**

4 Data and Methodology

4.1 Methodology

4.2 Workflow Overview

The general methodology for this work is described in figure 4.1. Each portion of this figure is discussed in detail in this section.

4.3 Assembly and Annotation

4.3.1 Assembly

Sequencing for the assembly process came in the form of Nanopore and Illumina sequence data. Nanopore data was not processed prior to assembly. Illumina sequencing data was filtered using Trimmomatic with filtering criteria as follows: SLIDINGWINDOW:4:28, LEADING:28, TRAILING:28, MINLEN:75. Only surviving paired-end reads were used for further analysis.

Genomic Nanopore sequences from DC1 and Tsth20 were assembled in to contigs using NextDenovo?? v2.5.0 and then polished with Illumina sequences using NextPolish?? v1.4.1. Assembly and polishing were both performed using default parameters.

4.3.2 Gene prediction with GeneMark-ES

Ab initio gene finding was performed using GeneMark-ES v4.71. Default parameters were used in all cases except for the fungal option, which was set to yes in order to use a GeneMark model specific to fungal genomes. Convenience options were also used to produce GFF3 output annotation files and an increased number of threads to reduce processing time.

4.3.3 Braker2

For evidence-based gene finding, Braker2 v3.0.2 was used with *Trichoderma reesei* selected as the reference or gold-standard genome to use as evidence. RNAseq datasets from *T. reesei* were downloaded from the NCBI

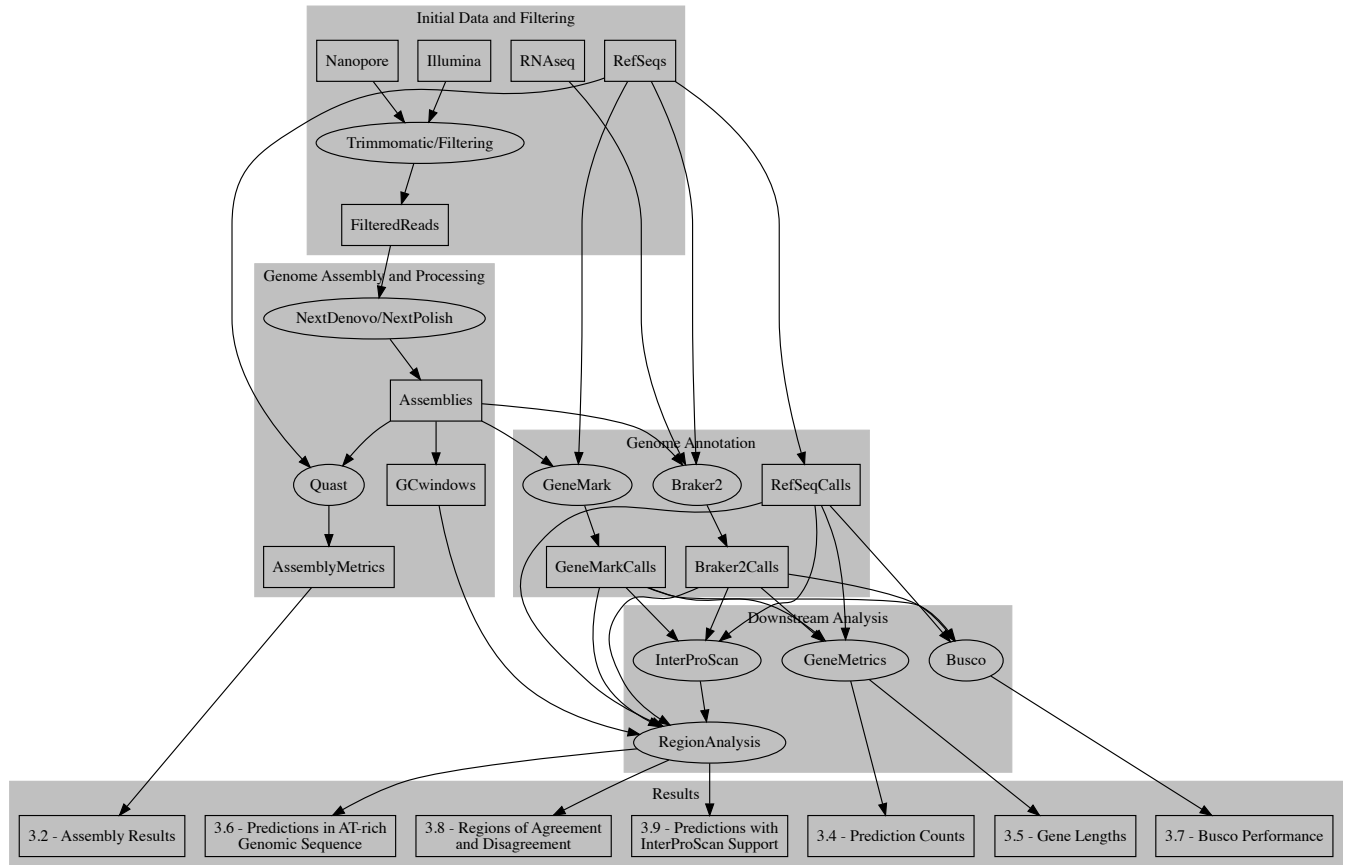


Figure 4.1: A flowchart of the methodology followed for this research. The workflow is broken up into sections based on the stage of the pipeline. Oval-shaped nodes represent steps involved in the processing of data, while rectangular nodes represent intermediate datasets and results.

short-read archive using the sra-toolkit and were not trimmed or filtered prior to their use with Braker2. Default parameters were used to train a Braker2 model on *Trichoderma reesei* data except in the case of the fungal option, which was used for this analysis for improved gene-finding performance in fungi. The Braker2 *T. reesei* model was then applied to all assemblies.

4.4 BUSCO Performance

To assess the general performance of gene-finders, BUSCO v5.7.1 was selected as a tool to determine a gene-finder's ability to predict a set of conserved orthologous genes. The BUSCO v5.7.1 Metaeuk pipeline was run using the Odb10 fungal lineage dataset to capture highly conserved genes in fungal genomes. This pipeline was applied to all genome assemblies used in this work. Used transcriptome mode... This needs to be discussed.

4.5 Region Identification

Feature Identification: To first understand how gene prediction tools perform in comparison to other gene prediction tools, we must identify features. This identification of features will help us describe the similarities, and differences between gene finding tools. A feature, in this context, is any feature stated within a Genomic Feature Format file (GFF) provided to the program, in which multiple GFF files can be provided. The definition of a feature, for this application, is an object that contains a contig ID, a start position, an end position and a strand property. In the context of features on different strands, start and stop positions of features are sorted based on left and right positions of the feature in respect to the reference sequence.

Region Identification: In addition to feature creation, we will also identify regions of overlapping features based on the predictions from each gene finding tool. These regions will help identify the agreements, or disagreements, between different gene-finding tools. A region, in this context, is a set of overlapping features, all of which overlap at least one other feature in the region. With each overlap, there will be an overlap type. These types can be defined based on Allen's Interval Calculus (reference), with the exception of features that start beyond the end point of the current region.

===== Example command for braker2:

```
/scratch/p2irc/p2irc_rsmi/cbe453/masters/software/braker2/BRAKER/scripts/braker.pl -gff3 -threads 60 -TSEBRA_PATH=/scratch/p2irc/p2irc_rsmi/cbe453/masters/software/braker2/tsebra/TSEBRA/bin/ -genome /path/to/sequence -species=TreeseiFungal -fungus -useexisting
```

BUSCO methodology (from research questions) The BUSCO method was applied using two BUSCO subsets, one generally applicable for fungi, and another targeting an evolutionary branch more closely related to *Trichoderma*.

Stats for length analysis (from research questions) The first statistical tool to be applied is ANOVA (analysis of variance) to compare the mean lengths genes predicted by each gene finding tool with the null hypothesis

being that the mean of predicted gene lengths should be the same across all tools considered. In addition to ANOVA, pairwise comparisons of the distributions using a Kolmogorov–Smirnov test is appropriate. The null hypothesis in this test would be that the gene lengths are sample from the same distribution.

Stats for binomial tests (from research questions) To do this, a binomial test will be used, with the null hypothesis being that the number of genes predicted in regions of normal and abnormal GC content should be proportional to the length of normal and abnormal GC content regions in the assembly. For example, if 30 percent of the genome is comprised of anomalous GC content, then we would expect 30 percent of predicted genes to be present in those regions. In addition to anomalous GC content, this test can be applied to repetitive content in assemblies as well.

Stats for regions (from research questions) From these results, Venn diagrams will be generated with Jaccard index calculated for each combination of gene finding tools. The region identification process can also be extended to include features identified by other tools, such as BLAST hits to validated gene models from other organisms and small RNAs. Chi2 goodness of fit tests can then be applied to counts of 'validated' gene predictions or other features with the same null hypothesis that gene finders should predict the same number of features.

4.6 Analysis of Results

After completion of the processing portion of this work, the results must be processed in a useful way, which includes both the biological implications of the gene calls as well as the computational, or gene finding features, of the the selected programs. To better understand how gene finders perform in these two classes, we must define an appropriate plan for analysis of the results produced so far. Currently, downstream analysis plan has been broken down into several sections.

4.6.1 Basic Analysis

Basic analysis of gene finding results is an important part of this research. Total gene, transcript and protein counts will be identified for each genome and gene finding tool combination. Comparing the general outputs of these programs will provide an idea of their performance in different *Trichoderma* genomes. In addition to these basic outputs, analysis will also be performed for the following: distribution of gene lengths, intersection of gene calls, smallRNAs and repetitive regions, shared gene content with a close fungal relative. Analysis for these results can be performed through simple shell scripting with grep and other unix tools, although processing through Python might provide results that are easier to reproduce with proper programming. Having one script with several modules that can be rerun at will would be easier to handle than multiple shell scripts. This thinking for processing will be applied to subsequent sections of this as well.

4.6.2 Distribution of Gene Lengths

One important aspect of gene finding tools to consider is the distribution of gene lengths predicted by each individual tool. Certain tools, such as GeneMark are based on pre-defined models, which may limit the length of predicted genes, while tools such as Braker2, which incorporate RNAseq data, may predict a wider distribution of gene lengths depending on the input dataset used. Regardless, the ability of a gene finding tool to predict a wider range of gene lengths can be useful if users are looking for short or larger genes. To help determine whether or not these tools find shorter genes, or small RNAs, the genomes of interest have been annotated using Infernal along with the Rfam database to identify small RNAs as a ground truth. These annotation results will also be included with results from other annotation processes further down the line. Again, these results can be produced with a Python script. The resulting data could then be used as input to violin plots for each genome and set of tools considered in this analysis process. Violin plots should provide a good visualization of gene lengths as well as the number of genes found with specific lengths. Means could also be compared statistically for genomes and the multiple tools considered as well.

Analysis of gene lengths was performed using a Python script. Combined predicted CDS sequences for each predicted gene were used as input for the total gene length. CDS sequences predicted by Braker2, were directly available in the output directories when the program was run. CDS sequences from GeneMark required extraction of the CDS sequences from the genome FASTA files. This process was performed using the gffread tool from the Cufflinks package. Predicted CDS sequences were loaded into Python using Biopython's SeqIO package. Sequence lengths were then placed in a list and analyzed using a combination of pandas and numpy. A log10 transformation was applied to the sequence lengths as the original distribution was heavily skewed due to long outlier CDS sequences. After transformation, the CDS length distribution appears as a normal distribution, although there are interesting troughs that occur in several of the peaks for several of the genomes considered. These troughs did not appear in a comparable Yeast reference dataset, although the log transformed data still appears to be a normal distribution.

4.6.3 Intersection of Gene Calls, smallRNAs and Repetitive Regions

Annotation of all three features in the title are important in assessing the ability of gene finding tools. Even more important, is the potential for overlap between gene calls and small RNAs as well as repetitive regions the genomes. As discussed in the previous subsection, the distribution of gene lengths predicted by a gene finding tool can be an important metric for users. Overlapping predicted genes from tools alongside the output from Infernal and the Rfam database may provide insight into whether or not these gene finding tools are able to predict RNAs of very short length. In addition to small RNAs, repetitive regions in *Trichoderma* genomes hold potential for recombination and gene content, although the inherent nature of these repetitive regions (low nucleotide diversity) suggests that gene content should be low, based on the nucleotides required for start and stop codons. Analysis of these intersections can be performed via bedtools or through biopython

(I believe). Again, having all processing steps included in one script as separate functions that can be called at whim will make further processing easier if changes need to be made.

4.6.4 Methodology for Identifying Overlapping Features

To analyze the results from multiple gene-finding tools, we must first define two conceptual topics.

Definition of a Feature: First, a feature, in the context of this research, is any item contained within a Genomic Feature Formatted file (GFF). Each feature contains a contig ID, a start position, end position, and a feature ID based on the information from the GFF file. These features will be used in the process of identifying regions, or overlapping features from prediction tools.

Definition of a Region: Secondly, a region is defined as any overlap between features relative to the reference sequence being considered. To identify regions, every feature from each GFF file being considered, is sorted by start position. For clarification, the start position is based on the left most position in the GFF file, regardless of the strand that the feature is predicted on. Once the features have been sorted by left position, the sorted features are iterated over to identify regions, as long as the left position of the next feature is consistent with the left position, within the left and right position, or equal to the right position of the current region. One drawback to this approach is that ideally, identification of overlap types based on Allen's interval algebra would be performed at this point. However, the methodology of initially sorting features based on left position somewhat prevents this process from happening. This implementation requires further processing of identified regions late on the process, simplifying the all to all comparison that would occur if all features were considered at once.

Identification of overlapping features results in different 'classes' of regions. A few basic cases are outlined in figure 4.2. The simplest of case is the a region where the gene finders agree unanimously on the gene (agreement currently means same start and end point).

4.6.5 Shared Gene Content with Closely Related Organisms

While considering novel gene calls can be useful, comparing those calls to a well-studied close relative can provide a rudimentary validation of the calls as a ground truth. This process will confirm that at least most of a closely related fungal genome's coding sequences are predicted and shared by the gene calls for *Trichoderma*. Results for this processing can be produced with a simple BLAST search and appropriate cutoff values (i.e. query coverage, percent identity, E-score, etc.). While running BLAST is a simple process, the selection of a closely related organism is more difficult. One initial choice would be to work with *Saccharomyces cerevisiae*, or bakers yeast, as it is extremely well studied and would be considered a model organism, similar to *Arabidopsis* and *Mus musculus*. However, *Saccharomyces cerevisiae* diverged evolutionarily millions of years ago, which may make it a poor candidate for a comparative analysis. The second candidate considered for comparison is *Fusarium avenaceum*, as it is also well studied and more closely related to *Trichoderma* than yeast, and has a genome similar in size to that of *Trichoderma* species, at roughly 40Mb. Finally, comparison

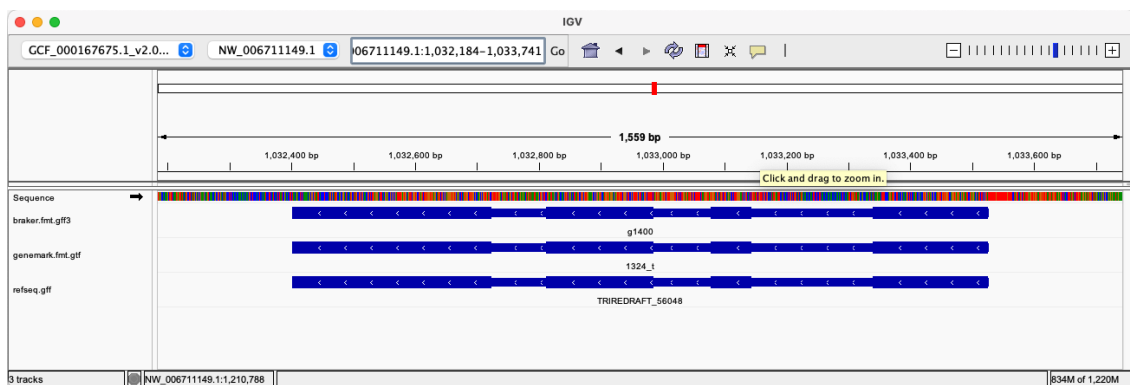
of assemblies and predicted genes to another *Trichoderma* strain is a reasonable approach. In this case, *Trichoerma atroviride* was selected as it is not included in the species used in the gene prediction portion of this analysis. From these assemblies, the RefSeq proteins (queries) from NCBI will be used in a tblastn search against each genome sequence from DC1, Tsth20, *T.reesei*, *T. harzianum*, and *T. virens* (subjects). Resulting BLAST hits will then be filtered based on suitable alignment coverage and identity, which will be determined by the reference sequence being considered. Total number of BLAST hits reported for each organism will provide information about completeness of assemblies and overall coverage of the gene/coding sequence space in the query sequences (need to be clear with language used for blast subjects and query). In addition, BLAST hits will be analysed with the region identification approach to identify coverage of protein and coding sequences in relation to gene predictions generated previously.

4.6.6 BUSCO Analysis

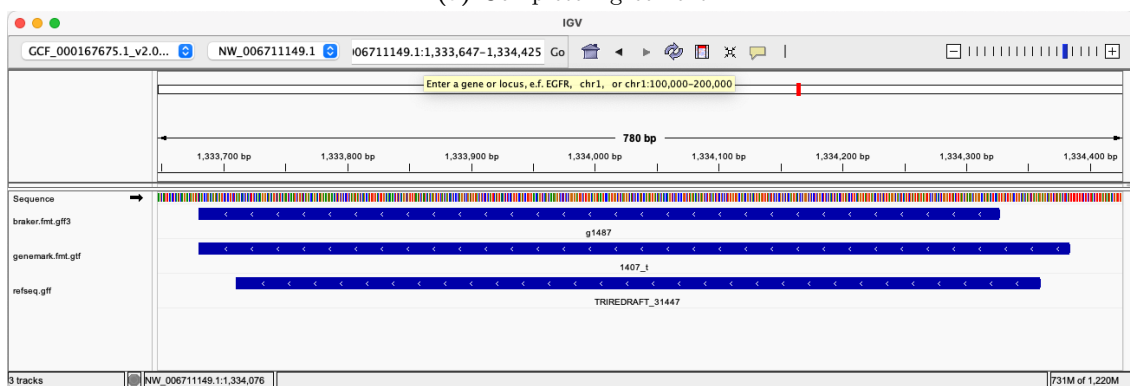
Another method for assessing the completeness of a set of predicted genes is Benchmarking Universal Single-Copy Orthologue (BUSCO) analysis[8]. BUSCO analysis is similar to analysis of overlapping or shared gene content with a close relative in that we are comparing the predicted gene sets to an existing standard or reference. With BUSCO analysis, the reference set has a far more strict definition. The datasets used for BUSCO analysis are based on single-copy orthologs generally found in a genome of interest. What this means is that BUSCO searches for single-copy genes that should be present in an organism based on the database selected for analysis. As an example in fungi, if one were interested in assessing the completeness of their annotated genes in a similarly related fungi, there should be a set, or subset, of single-copy genes present in the new annotation that are expected to be present after evolutionary divergence(...). This can be thought of as similar to a 'core' gene set. Results from BUSCO analysis are typically reported in a percentage of the gene set included in the BUSCO dataset. Percentages of single and duplicated hits are reported as well. While a high reported coverage of the BUSCO dataset is considered good, it is not fully indicative of excellent gene finding performance

4.6.7 Comparative Genomics

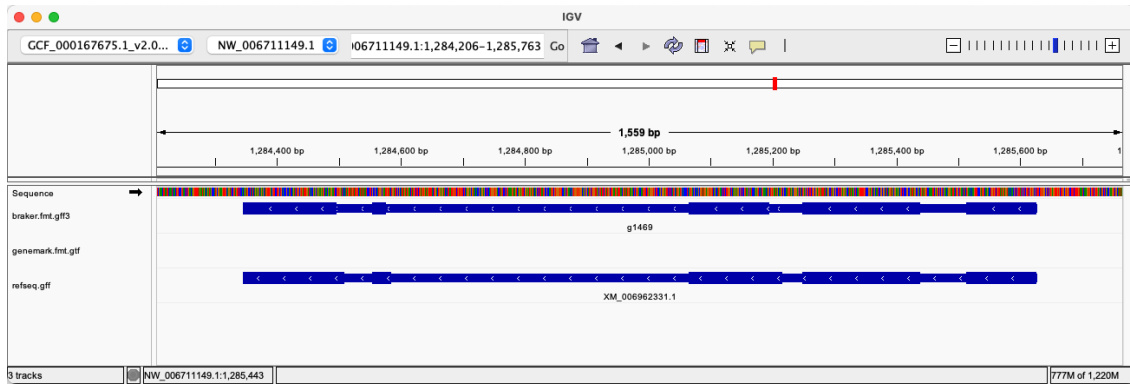
With the data produced by this research, it is possible to perform some comparative genomics (time permitted), mostly related to the assemblies generated during this work along with the RefSeq genomes included from NCBI. Mummer is a potential tool to use for all to all genome alignments, although there may be difficulty in the ordering of contigs/scaffolds/chromosomes when performing these alignments. This work is not necessarily required but would be interesting from a biological perspective to identify rearrangements, inversions and such.



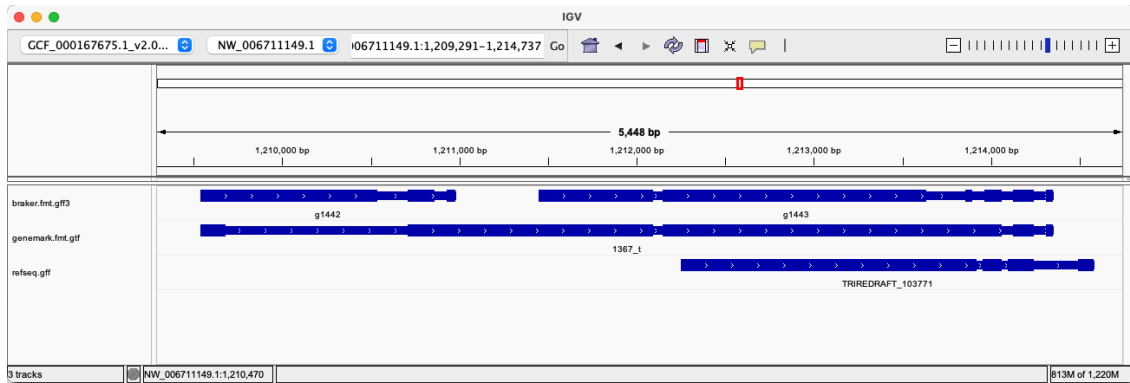
(a) Complete Agreement



(b) Start/Stop Disagreement



(c) Missing Prediction



(d) Complete Disagreement

Figure 4.2: Several visual examples of regions using IGV. **a)** Region where all prediction tools are in agreement. **b)** Prediction tools agree that gene is present, but not on the exact start and/or stop positions. **c)** A region where one tool does not predict a gene while the others do. **d)** A region with a combination of disagreeing predictions.

5 Results

5.1 Assemblies of DC1 and Tsth20

For general assembly metrics of DC1 and Tsth20, the QUAST tool was used. Results from QUAST are shown in figure 5.1, from which we can make several observations. In DC1 and Tsth20, the total contig counts are an order of magnitude smaller when compared to the other NCBI RefSeq assemblies, indicating highly contiguous assemblies from nextDenovo and nextPolish. This is likely due to the use of long-read sequencing used in the assemblies of DC1 and Tsth20. The total assembly lengths are similar, ranging from 38Mb to 42Mb, except in the case of *T. reesei*, which is known to have a significantly smaller genome length [6] at roughly 33Mb. The largest contig size for each assembly varies greatly. DC1 and Tsth20 have the largest contigs of all assemblies being considered, which is again likely due to the inclusion of long-read sequencing data in the assembly process. The N50 values for all assemblies are above 1Mb, with DC1 and Tsth20 N50s being at minimum three times larger than others assemblies. Results from this table indicate that the assemblies of DC1 and Tsth20 are more contiguous than the assemblies of *Trichoderma reesei*, *harzianum* and *virens* also considered in this analysis. While contiguity is not the sole indicator of genome quality, it does provide confidence in the quality of the input data and resulting assemblies. In general, the assemblies of DC1 and Tsth20 are of similar length to existing *Trichoderma* assemblies and the number of contigs reported match the number of ‘chromosome’ scale contigs reported in other work.

During initial investigation of the sequences used as input to the assembly process, we observed that the reads contained abnormal ratios of GC content. To see if this observation extended to the assemblies as well, 250 bp sliding windows were used to calculate GC content for all assemblies included in this analysis. The

Strain	Total Contigs	Total Length	Largest Contig	GC%	N50	L50
DC1	8	38.6 Mb	11.49 Mb	47.97	5.69 Mb	3
Tsth20	7	41.58 Mb	8.02 Mb	47.33	6.52 Mb	3
<i>T. harzianum</i>	532	40.98 Mb	4.08 Mb	47.61	2.41 Mb	7
<i>T. virens</i>	93	39.02 Mb	3.45 Mb	49.25	1.83 Mb	8
<i>T. reesei</i>	77	33.39 Mb	3.75 Mb	52.82	1.21 Mb	9

Table 5.1: General assembly metrics produced by QUAST (a genome quality assessment tool).

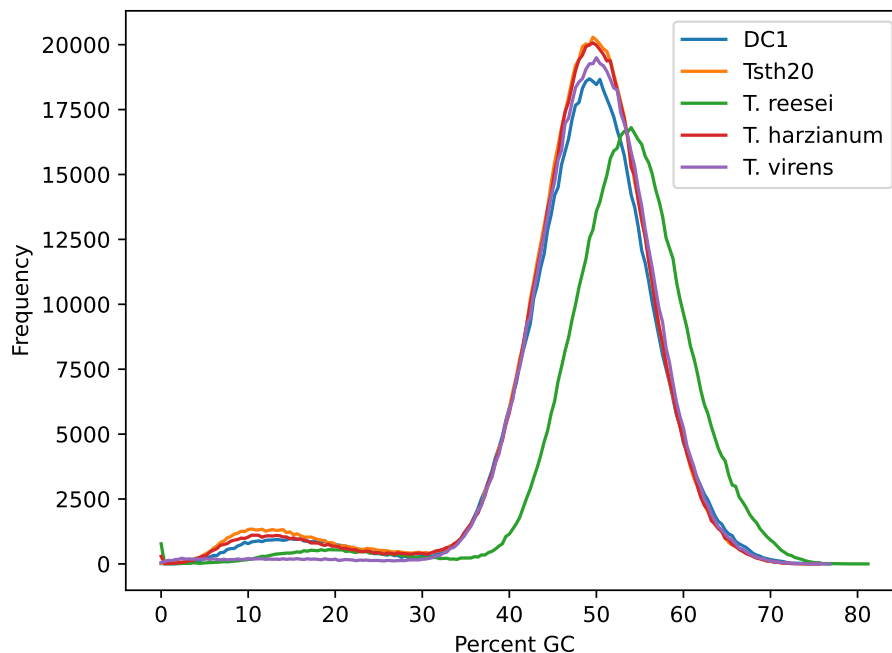


Figure 5.1: Plots showing the frequency of GC values calculated from sliding windows for each assembly.

results of this analysis are shown in figure 5.1. Of the included assemblies, anomalous GC content in the form of AT-rich sequences were identified in DC1, Tsth20, *T. reesei* and *T. harzianum*, with *T. virens* deviating from the other assemblies showing very few AT-rich windows. Anomalous GC content is visualized on the left tails of the distributions with a local peak around sequences containing 10 percent GC content. In addition to the confirmation of increased AT-rich sequence content in most assemblies, it appears that the distribution of GC content in *T. reesei* differs from the other assemblies. The curve of GC content for *T. reesei*, visualized in green in 5.1, lies farther to the right, indicating more GC content, or fewer AT-rich windows, in its assembly. While the left tail of the curve also shows an increase in AT rich sequence composition, it is shifted farther right than other *Trichoderma* assemblies. Investigation of these anomalous regions is continued in section ...

5.2 Profiling Gene Finding Tools

While Braker2, GeneMark and RefSeq all provide lists of possible genes for a provided reference, the implementation of each tool is different, requiring more or less effort to install and run depending on the tool used. The computing platform used in this research is hosted and managed by University of Saskatchewan services, which is modelled around the HPC platform used by the Digital Research Alliance of Canada and software is managed similarly.

First, we will briefly discuss the RefSeq annotation process. RefSeq annotation is only applied to data that is submitted to NCBI. The RefSeq Eukaryotic Genome Annotation Pipeline[11] is a genome annotation process developed and maintained by NCBI. The pipeline is not directly publicly available to public users, and requires submission of data to NCBI. Once data is submitted to NCBI, the RefSeq annotation pipeline may be applied upon request only if the genome is the highest quality assembly for the species in question or if the genome is of significant interest to the scientific community, limiting reach of the annotation process to many users. The pipeline supplies existing RNAseq, CDS and protein sequences to NCBI's in-house gene prediction tool Gnomon, which produces trained models for gene prediction. While the tools used for alignment and processing of supporting sequence information are listed, the inner workings of Gnomon are not well documented, at least from the public perspective, and I was unable to find Gnomon in any compilable or executable form during my search. Recreation of the RefSeq pipeline would prove extremely challenging if not impossible without supporting information. Run times for this pipeline are difficult to determine due to the hidden nature of the pipeline, unknown compute resources and varying quantities of data used. The RefSeq annotation process produces comprehensive outputs, including CDS sequences, translated CDS, RNA from genomic sequences, proteins, feature counts and tables, and finally GFF and GTF formatted annotation files for these features.

Next we will discuss the handling, installation, and running of both Braker2 and GeneMark packages. Several points will be discussed for each tool, with those points being sourcing and downloading, components and prerequisites, installation, execution, and output. GeneMark[7] is a gene finding tool developed by the Georgia Institute of Technology with packages prepared for Linux and MacOS. It is provided as licensed product in the form of a package which can be downloaded from their website after submitting a form. Once the necessary information is submitted, the user is provided with a key that must be placed in the appropriate location once the software is downloaded and unpacked. The core controlling methods of GeneMark are written in Perl, accompanied by several Python scripts and compiled executables. GeneMark was tested by the developers with Perl version 5.10, and Python 3.3. A number of Perl dependencies are also required, which can be installed via YAML. The user will have to know which implementation of GeneMark they are wanting to use for their application, as GeneMark has several variations it can run depending on the desired application. In this work, the GeneMark-ES variant of GeneMark was executed, as it is the self-training *ab initio* GeneMark method for eukaryotic organisms. Options required by GeneMark at runtime are documented in the help message, and simple enough that any user with familiarity of bioinformatics tools should be able to run GeneMark, although documentation for use is only provided by the help message when running the program and not online. In regards to run-time, running the GeneMark-ES pipeline on DC1 with 56 threads finished in 16 minutes. Upon completion, GeneMark produces a GTF or GFF file of predicted genes as well as a number of other outputs related to the run.

Braker2[2] is hosted on GitHub as a repository that receives relatively frequent updates with Braker3 being released while working on this thesis. Braker is maintained by Katharina Hoff from the Univer-

sity of Greifswald and is available under the Open Source Artistic License. Installation of the repository is a straightforward pull from GitHub. As with GeneMark, Braker2 uses a combination of Perl, Python and other executables in its regular use. Downloading the repository itself is not enough for execution, as Braker2 relies on a number of dependencies and bioinformatics tools including Perl and (Perl dependencies), Augustus, BamTools, BedTools, GeneMark, StringTie, GFFRead and a few others. Manual installation of these dependencies would be difficult, time consuming and in general advised against. In this case, many of Braker2's requirements are satisfied by modules already included in the environment, making installation relatively simple if you know the ins and outs of the Digital Research Alliance of Canada's software stack. This case still required installation of some Perl modules in addition to loading necessary modules. Alternatively, one could use a package manager like Anaconda or Minoconda to handle installation of packages. This is perfectly reasonable, but also requires knowledge specific to Anaconda, which can be complicated and frustrating for users with little software management experience. The newly released Braker3, also includes a containerized version of the software, allowing users to build and execute Braker3 with ease in its own environment. Once installation is finished, the Braker2 pipeline is relatively straightforward to run as well, with excellent documentation included both online and through the built in help message. In this research, the Braker2 pipeline was run in two modes. The first mode is a training mode, where sequence files are supplied to Braker2 to train a gene-calling model. The training and gene finding steps are run as part of the same command, and a model built using the training data is saved for bookkeeping and future use. The training was performed using roughly 145 million Illumina paired end RNAseq reads on the *Trichoderma reesei* genome. The training, including RNAseq alignments, and gene finding pipeline in this case took 1 hour and 17 minutes using 60 threads. Applying the Braker2 trained gene finding model to DC1 with 60 threads took 21 minutes to complete. Run times will of course vary depending on processing power available to the end user, but in the case of *Trichoderma* genomes, users can expect quick results with relatively little computing power. Once annotation is complete, Braker2 produces a GFF file containing predicted genes along with CDS sequences and amino acid sequences their protein products. Braker2, when trained with RNAseq data, includes an option to predict UTR regions, but it is experimental and is not performed by default and is not included in these runs.

In summation, Braker2 and GeneMark are not direct plug-and-play software packages. Users should expect to encounter issues when getting these programs running in addition to normal downloading and unpacking of software packages so some expertise is recommended. Neither Braker2 nor GeneMark require users to compile software, however Braker2's dependencies may require additional compilation and attention. Once installed, both tools are relatively simple to use with documentation available for both on the commandline and excellent documentation available for Braker2 on their GitHub page. Outputs from both tools are similar although Braker2 has the ability to output coding and amino acid sequences for downstream processing. Both tools run in reasonable amounts of time, where in the case of smaller genomes such as *Trichoderma*, users can expect results within a few hours to a day depending on number of computing cycles available to

Assembly	Braker2		GeneMark		RefSeq	
	Genes	mRNA	Genes	mRNA	Genes	mRNA
DC1	8546	8637	11353	11353	N/A	N/A
Tsth20	8784	8858	12362	12362	N/A	N/A
<i>T. reesei</i>	9659	10175	9196	9196	9109	9118
<i>T. harzianum</i>	8314	8385	12164	12164	14269	14090
<i>T. virens</i>	7801	7863	11866	11866	12405	12406

Table 5.2: Number of genes predicted by each gene finder for each *Trichoderma* genome.

them.

5.3 Initial Gene Finding Results

Counts of genes predicted by Braker2, GeneMark and RefSeq are shown in table 5.2. Immediately we see that Braker2 predicts far fewer genes in all assemblies, except in the case of *Trichoderma reesei*. This is possibly due to the effects of training the Braker2 gene model using data from *Trichoderma reesei*. Given the shorter length of the *T. reesei* assembly, and subsequently fewer genes present, the trained model may predict fewer genes in other assemblies. Regardless, there is a significant difference in the number of genes predicted by Braker2 in comparison to GeneMark and RefSeq. The number of genes predicted by GeneMark and RefSeq are similar, except in the case of *T. harzianum*, in which RefSeq predicts roughly 17% more genes than GeneMark. Braker2 consistently predicts more transcripts than GeneMark and RefSeq. RefSeq also appears to predict isoforms but in fewer numbers than Braker2. Transcript prediction counts in *T. harzianum* from RefSeq are also interesting, with RefSeq predicting fewer transcripts than genes. Why this occurs is unknown but may warrant further investigation.

5.4 Distribution of Predicted Gene Lengths

To better understand and compare the distributions of gene lengths predicted by Braker2, GeneMark, and RefSeq, the cumulative density function for the lengths of CDS sequences for each gene finding tool are shown in figure 5.2, 5.3 and 5.4. The \log_{10} values of gene lengths were used for a better visualization of the distributions. In DC1, the curves from Braker2 and GeneMark follow each other closely, with the only variation being genes of short length, where Braker2's curve extends beyond that of GeneMark, indicating that Braker2 predicts more shorter genes than GeneMark. In the case of Tsth20, the curves are nearly identical. In *T. reesei*, we see disagreement in the curves for shorter genes, with Braker2 appearing to predict a greater amount of shorter genes than GeneMark and RefSeq. The upper portions of the curves trend toward similar predicted gene lengths. In *T. harzianum*, RefSeq deviates from GeneMark and Braker2, predicting

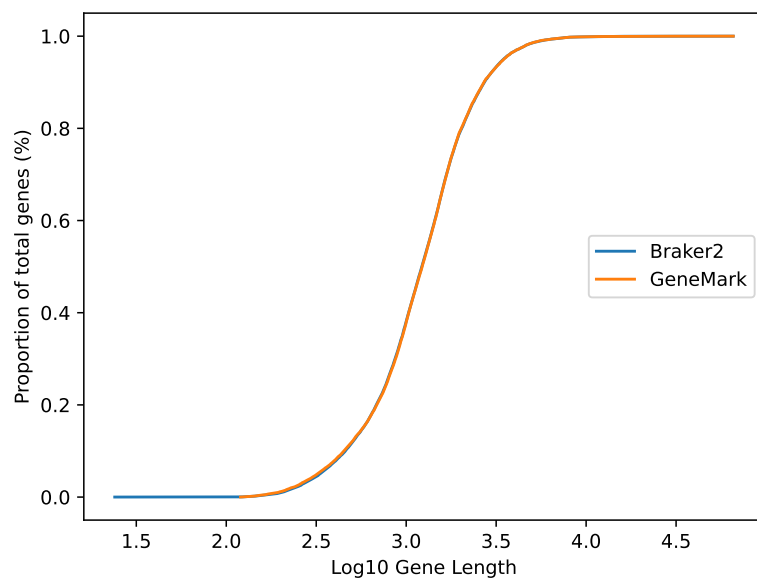
Genome	Tool #1	Tool #2	P -value
DC1	Braker2	GeneMark	0.999
Tsth20	Braker2	GeneMark	0.965
<i>T. reesei</i>	Braker2	GeneMark	9.481^{-07}
<i>T. reesei</i>	GeneMark	RefSeq	0.002
<i>T. reesei</i>	Braker2	RefSeq	1.340^{-07}
<i>T. harzianum</i>	Braker2	GeneMark	0.863
<i>T. harzianum</i>	GeneMark	RefSeq	4.313^{-52}
<i>T. harzianum</i>	Braker2	RefSeq	4.674^{-55}
<i>T. virens</i>	Braker2	GeneMark	0.635
<i>T. virens</i>	GeneMark	RefSeq	7.352^{-12}
<i>T. virens</i>	Braker2	RefSeq	1.794^{-09}

Table 5.3: Table of P -values from two-sided two-sample Kolmogorov-Smirnov tests between gene finding tools.

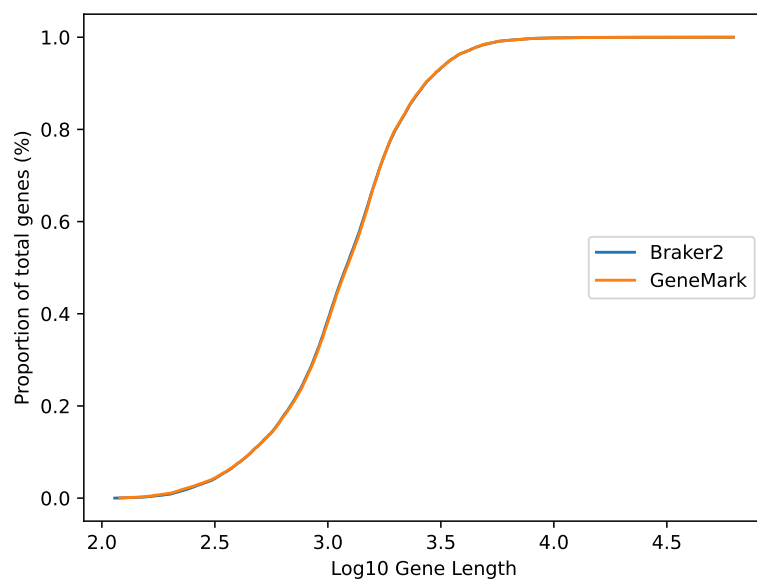
more genes of short length, while Braker and GeneMark appear to be in near-complete agreement except in the case of very short genes. Finally, in *T. virens*, we see the RefSeq curve predicting shorter genes once again, although the deviation is not as drastic as in *T. harzianum*. It also appears that GeneMark predicts the shortest genes in *T. virens*, deviating from the other assemblies where Braker2 always predicts the shortest genes. From these plots, we can say that visually, gene finding tools appear to predict different lengths of genes. We also observe that Braker2 typically predicts the shortest genes of all three gene finding methods.

To confirm these observations statistically, two-sided two-sample Kolmogorov-Smirnov tests were performed using the \log_{10} transformed gene lengths and are presented in table 5.3. In the cases of DC1 and Tsth20, we see that in agreement with figure ??, Braker2 and GeneMark do not produce statistically different lengths of genes, which is interesting considering that the Braker2 includes experimental evidence for another assembly while GeneMark does not. In *T. reesei*, while RefSeq and GeneMark do not reject the null hypothesis when compared, Braker2’s predicted gene lengths are significantly different than both RefSeq and GeneMark, which is also confirmed visually in the CDF plots above. The same cannot be said for *T. harzianum* and *T. virens*, where RefSeq is significantly different from both GeneMark and Braker2, which are not significantly different from each other. It is also notable that RefSeq and GeneMark predict similar gene lengths in *T. reesei* but not in *T. harzianum* and *T. virens*.

It can clearly be stated that these gene finding tools predict different lengths of genes, particularly in *T. reesei*, *T. harzianum* and *T. virens*. Why that may be the case is difficult to answer without deeper investigation. There is clearly an underlying difference between RefSeq and the other gene finding tools. Braker2 and GeneMark tend to be in agreement, except in the case of *T. reesei*, which Braker2 was specifically

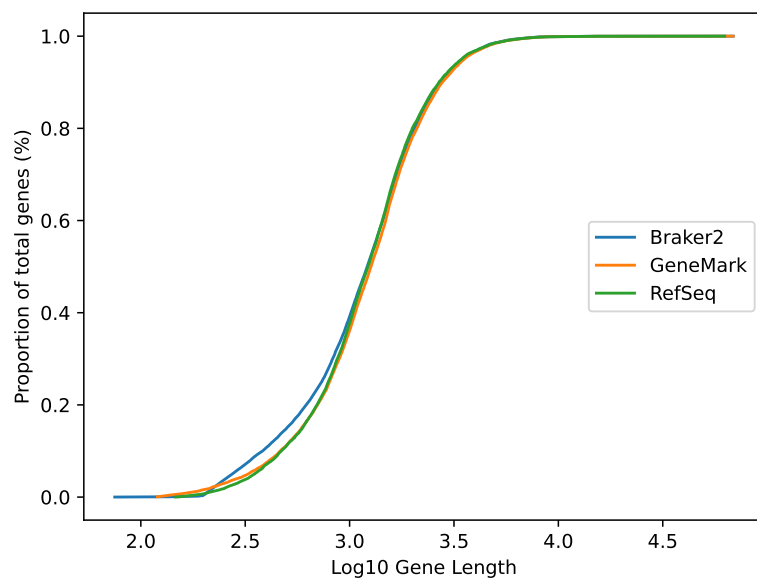


(a) DC1

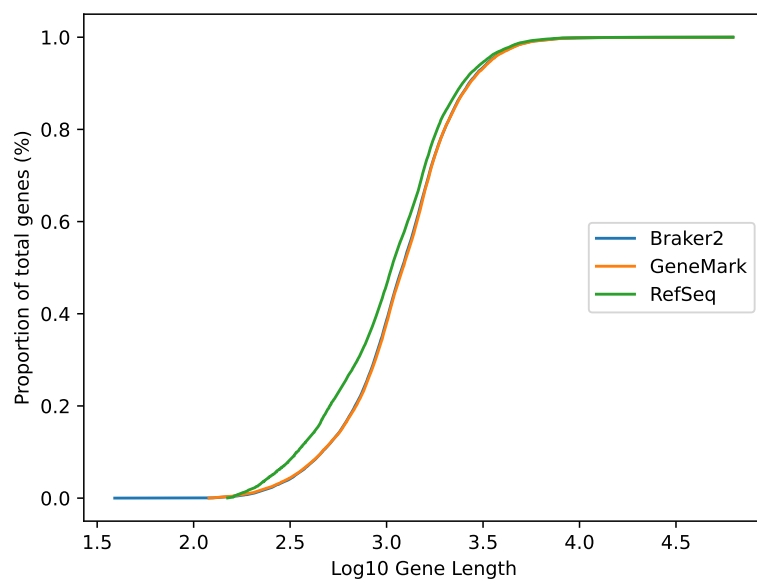


(b) Tsth20

Figure 5.2: Plots of the cumulative density function for CDS lengths produced by each gene finding tool applied to DC1 and Tsth20

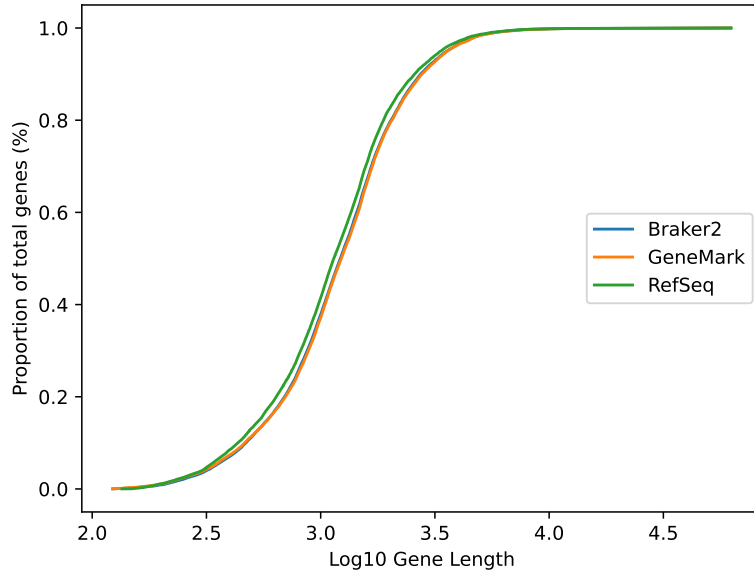


(a) *T. reesei*



(b) *T. harzianum*

Figure 5.3: Plots of the cumulative density function for CDS lengths produced by each gene finding tool applied to *T. reesei* and *T. harzianum*.



(a) *T. virens*

Figure 5.4: Plots of the cumulative density function for CDS lengths predicted by each gene finding tool when applied to *T. virens*.

trained for. We observe that when gene finders are applied to the assemblies from which their training data originated, they tend to predict shorter genes. Conversely, we observe that when a gene finding tool trained with experimental evidence is applied to a different *Trichoderma* assembly, the lengths of predicted genes do not significantly differ from an *ab initio* gene finder like GeneMark, except in the case of RefSeq’s predictions on *T. reesei*.

5.5 BLAST Results

Results from the T-BLAST-N runs are presented in table 5.4. Initial BLAST results appear promising for both the *T. atroviride* and *Fusarium* datasets. All assemblies considered contain at minimum 89% of the reference protein sequences in the case of *T. atroviride* and a minimum of 75% in the case of *Fusarium*. In the case of *S. cerevisiae*, a minimum of 57% of reference proteins matched. The decreasing percentage of hits reported coincides with increasing distances in the evolutionary tree. These results provide rough validation that the assemblies contain potential for protein coding sequences.

Reference	Ref. Proteins	DC1	Tsth20	<i>T. reesei</i>	<i>T. harzianum</i>	<i>T. virens</i>
<i>T. atroviride</i>	11807	11552	11080	10601	11081	11078
<i>Fusarium</i>	13312	10327	10429	10064	10434	10490
<i>S. cerevisiae</i>	6014	3537	3517	3445	3509	3500

Table 5.4: tBLASTn hits from reference protein sequences to selected assemblies of interest. Hits are reported if the alignment length is greater than 30% of the reference protein length and if 30% of the aligned length have identical matches.

5.6 BUSCO Results

The results of BUSCO analysis using the fungal subset provided by BUSCO are presented in table 5.5. Results from BUSCO indicate that all gene sets considered in this analysis have a BUSCO completeness of 99.2% or higher, with a maximum Completeness of 99.9% for some gene sets. In general, Braker2 and RefSeq have the most BUSCO complete sets of gene predictions for the three tools considered. Interestingly, Braker2 produces far more duplicated BUSCO matches than both GeneMark and RefSeq. Examining the BUSCO output logs, this appears to be due to Braker2 producing more than one RNA for some genes predictions, resulting in multiple similar proteins. In general, all gene finders perform exceptionally well in regards to BUSCO performance. While these results do not capture the entire set of genes possibly present in these *Trichoderma* assemblies, they do confirm that the gene finders are at minimum predicting evolutionarily conserved fungal genes.

While BUSCO matches are a good metric for general performance of gene finders, it is also important to investigate BUSCO proteins without matching gene predictions. Tables 5.6, 5.7 and 5.8, show breakdowns of genes missed by each gene finder across the *Trichoderma* assemblies. Braker2 misses four unique proteins across the five *Trichoderma* assemblies, with only one protein missing in more than one assembly. This protein in particular represents a formyl transferase protein. GeneMark predictions miss six unique BUSCO proteins, with two proteins missing in more than one assembly. These proteins represent a formyl transferase, which was missed in four of the five assemblies, and a ubiquitin-conjugating enzyme, which was missed in all five assemblies. RefSeq, being the gene finder with the most BUSCO complete set of gene predictions, misses only three unique BUSCO proteins in the three assemblies. Of those three proteins, two of them are missed twice. Those missing proteins represent a YEATS protein domain and Midasin protein.

Braker2, GeneMark and RefSeq all demonstrate excellent coverage of the BUSCO fungal protein set, indicating that these gene finders are capable of predicting genes that are expected to be present in these assemblies. From this we can say that the foundations of the underlying gene models used by each gene finder are solid. Braker2 produces more duplicate matches than GeneMark and RefSeq, but this is likely due to multiple isoforms of possible genes being present in the input data. Despite excellent coverage of the BUSCO fungal proteins, all three gene finders miss some BUSCO proteins in their predictions. GeneMark misses the

Strain	Complete	Single	Duplicated	Fragmented	Missing	No. markers
DC1	99.5	80.2	19.3	0.1	0.4	758
Tsth20	99.9	81.7	18.2	0.0	0.1	758
<i>T. harzianum</i>	99.7	80.2	19.5	0.0	0.3	758
<i>T. virens</i>	99.8	79.0	20.8	0.1	0.1	758
<i>T. reesei</i>	99.9	85.5	14.4	0.1	0.0	758

(a) Braker2

Strain	Complete	Single	Duplicated	Fragmented	Missing	No. markers
DC1	99.2	98.8	0.4	0.3	0.5	758
Tsth20	99.8	99.1	0.7	0.0	0.2	758
<i>T. harzianum</i>	99.6	98.9	0.7	0.0	0.4	758
<i>T. virens</i>	99.7	99.2	0.5	0.1	0.2	758
<i>T. reesei</i>	99.6	99.5	0.1	0.0	0.4	758

(b) GeneMark

Strain	Complete	Single	Duplicated	Fragmented	Missing	No. markers
<i>T. harzianum</i>	99.9	99.2	0.7	0.0	0.1	758
<i>T. virens</i>	99.5	98.8	0.7	0.3	0.2	758
<i>T. reesei</i>	99.8	99.5	0.3	0.0	0.2	758

(c) RefSeq

Table 5.5: Results from BUSCO using the fungal analysis option organized by gene finding tool.

BUSCO ID	Annotation	DC1	Tsth20	<i>T. reesei</i>	<i>T. harzianum</i>	<i>T. reesei</i>
195619at4751	Pyridoxal phosphate-dependent transferase	X	✓	✓	✓	✓
285254at4751	Aminoacyl-tRNA synthetase	✓	✓	✓	X	✓
348020at4751	Formyl transferase	X	X	✓	X	✓
497024at4751	Zinc finger C2H2-type	X	✓	✓	✓	✓

Table 5.6: The presence or absence of all BUSCO IDs missed by Braker2 in each *Trichoderma* assembly.

BUSCO ID	Annotation	DC1	Tsth20	<i>T. reesei</i>	<i>T. harzianum</i>	<i>T. reesei</i>
195619at4751	Pyridoxal phosphate-dependent transferase	X	✓	✓	✓	✓
285254at4751	Aminoacyl-tRNA synthetase	✓	✓	✓	X	✓
348020at4751	Formyl transferase	X	X	X	X	✓
438731at4751	LSM domain	✓	✓	X	✓	✓
470813at4751	Ubiquitin-conjugating enzyme	X	X	X	X	X
497024at4751	Zinc finger C2H2-type	X	✓	✓	✓	✓

Table 5.7: The presence or absence of all BUSCO IDs missed by GeneMark in each *Trichoderma* assembly.

BUSCO ID	Annotation	DC1	Tsth20	<i>T. reesei</i>	<i>T. harzianum</i>	<i>T. reesei</i>
494at4751	Midasin	N/A	N/A	X	X	✓
315802at4751	tRNA dimethylallyltransferase	N/A	N/A	✓	✓	X
352224at4751	YEATS	N/A	N/A	X	✓	X

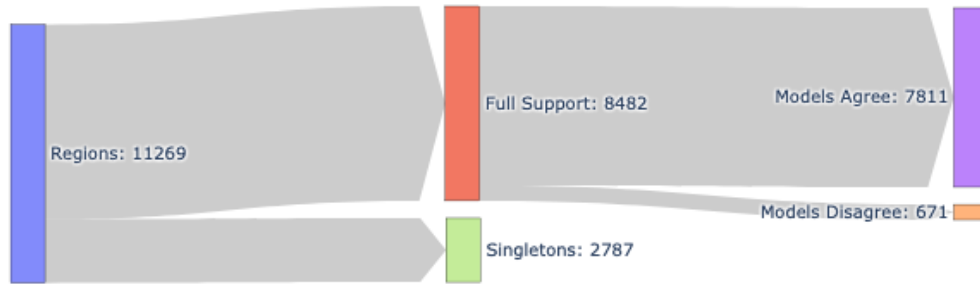
Table 5.8: The presence or absence of all BUSCO IDs missed by RefSeq in each *Trichoderma* assembly.

most proteins and in particular struggles with predicting a formyl transferase and a ubiquitin-conjugating enzyme. Braker2 also appears to have difficulty predicting a formyl transferase just as GeneMark did. RefSeq misses the fewest BUSCO proteins and does not appear to systematically miss certain proteins, although it is hard to draw a conclusion with only three assemblies considered. It is also worth noting that RefSeq misses completely different proteins than the other gene finders while Braker2 and GeneMark do share some missed proteins.

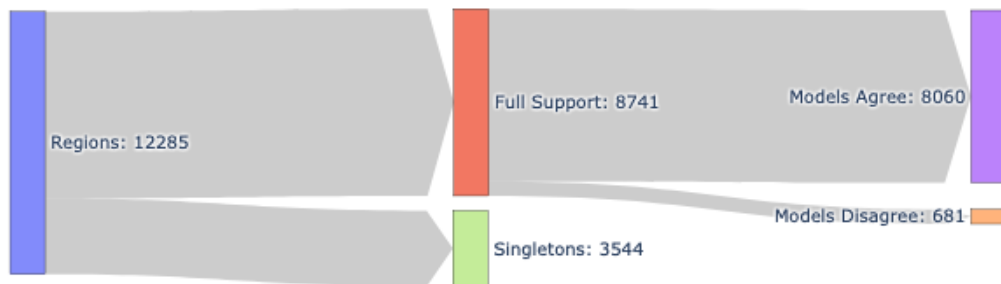
5.7 Region Identification

Visual breakdowns of the types of regions identified and their counts for each *Trichoderma* assembly are shown in figure 5.5. We will first discuss the types of regions, beginning with fully supported regions. These regions, labelled ‘Full Support’, are sections of genomic sequence where each gene finder agrees that a gene is present in some form. These fully supported regions are then broken down into two categories, based on whether or not the models from each gene finder agree on the start and/or stop positions of the gene model. Regions that have support from more than one gene finder, but not all, are labelled regions with ‘Partial Support’. These regions are also broken down into two sub-regions based on whether or not the gene predictions agree on the start and/or stop positions of the gene. Regions with support from only one gene finder are labelled as singletons.

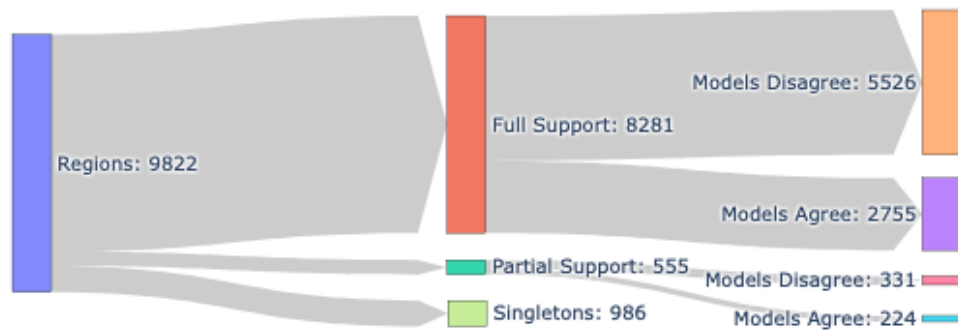
Looking at DC1 and Tsth20 in figure 5.5, it appears that Braker2 and GeneMark predict genes in the



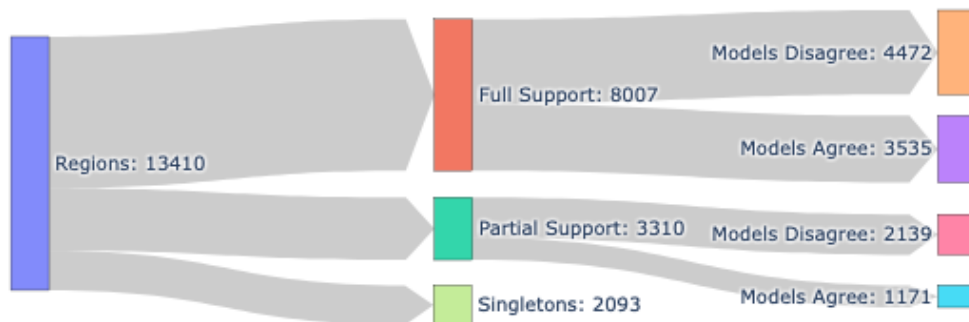
(a) DC1



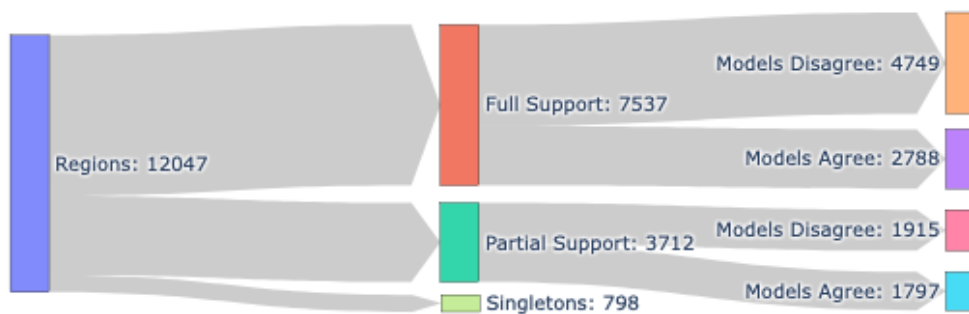
(b) Tsth20



(c) *T. reesei*



(d) *T. harzianum*



(e) *T. virens*

Figure 5.5: Figures showing breakdowns of genomic regions identified by the region finding process. Regions, in blue, are categorized based on support from gene finders. Regions with supporting predictions from all gene finders included in this analysis are labelled with ‘Full Support’ and colored red. Fully supported regions are then broken down into regions where gene models agree on the start and stop positions of the genes (purple), and those that do not (orange). Regions labelled with ‘Partial Support’ (turquoise) are regions with supporting gene predictions from more than one gene finder, but not all. Partially supported regions are also broken down into regions in which gene finders agree on the start and stop positions of the gene (cyan), and those that do not agree (pink). Regions with gene predictions from only one gene finder are labelled as singletons (green).

same regions in the majority of cases. For regions with full support, the models also tend to agree on the start and stop positions of the gene in that region. This is not generally the case as we will see later. There are no regions with partial support for DC1 and Tsth20, as there are only two gene finders considered, leaving only complete agreement or disagreement. *Trichoderma reesei* contains the fewest number of regions, which seems to scale appropriately with the total number of predicted genes. The vast majority of the regions are fully or partially supported by Braker2, GeneMark and RefSeq, with only 10 percent of the regions being single predictions. The most interesting thing here is the number of fully supported regions that disagree on start and stop positions of the gene(s) in each region. There is clearly a difference in the gene models being produced by these gene finders. If there is also more disagreement on the start and stop positions of a gene, then there is likely disagreement on the number and location of exons and introns within the gene model as well. In the case of partially supported regions, there is more disagreement than agreement, but that may come as less of a surprise as there is already disagreement on the presence by definition. Gene finding behaviour in regions from *T.harzianum* and *T. virens* differ from the other assemblies in the split between fully and partially supported regions. There seems to be fewer regions with full support from all gene finders and the reason why is unclear. The gene models in each region, whether fully or partially supported, still tend to disagree on start and stop positions of the genes more often than agree.

It is also worthwhile investigating some potentially interesting cases of strange gene calls in regions. One such case is when a region contains more than three individual predicted genes. The null hypothesis, so to speak, is that if all gene finders agree on the presence of a gene in a region, then one should expect only three predictions in that region. We observe that this is not always true. Cases of more than three gene predictions in a region were present in regions from all processed assemblies. Figure 5.6 shows an example of one of these regions, in which the single gene predicted by RefSeq spans multiple gene predictions from both Braker2 and GeneMark. In the case of DC1 and Tsth20, there were very few regions that matched this scenario, with 19 and 6 regions matching respectively. Conversely, *T. reesei*, *T.harzianum* and *T.virens* contain many such regions, with assemblies reporting 546, 899 and 521 regions with greater than three gene predictions respectively. While having predictions from each gene finding tool present in a region is a strong indicator for the presence of a gene, having more than one gene prediction per gene finder raises questions about which model (or models) is correct and why disagreement exists.

Another interesting set of criteria to investigate is whether or not gene finders always predict genes on the same strand within a region. We observe that regions containing predictions on different strands do exist, and are observed in predictions from all assemblies included in this analysis. Figure 5.7 shows an example of a region containing gene predictions on opposing strands. As in the case of regions with more than three gene predictions, DC1 and Tsth20 report fewer mixed strand regions with DC1 reporting 29 regions and Tsth20 reporting 46. *T. reesei*, *T. harzianum* and *T. virens* report more regions in which this property is true, with region counts being 203, 533 and 293 respectively. Under the assumption that gene finders should predict the same genes on the same strands, it is unexpected to find so many of these cases, and will require further

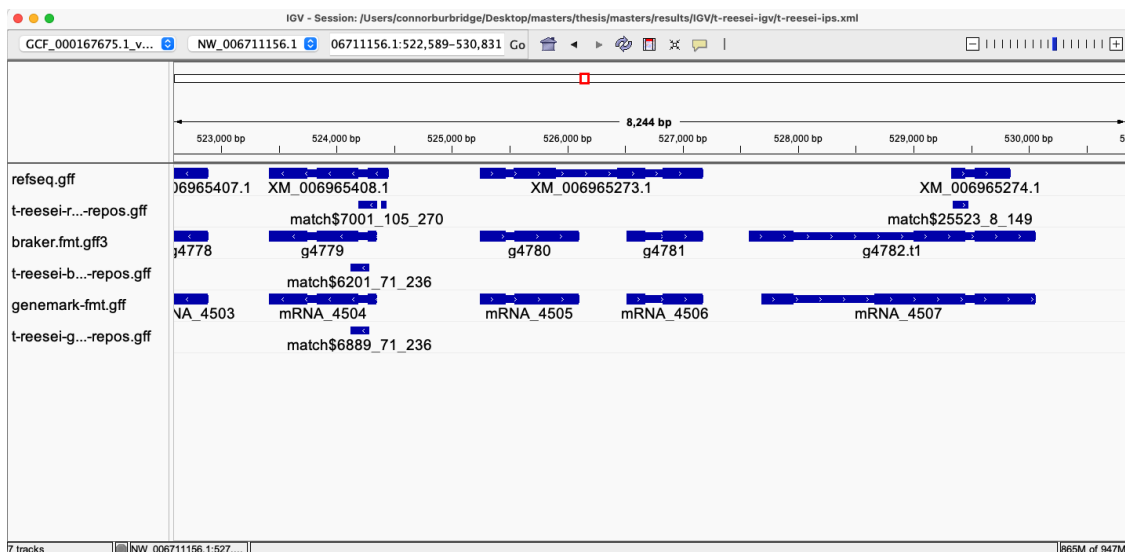


Figure 5.6: An IGV screenshot from *T. reesei* showing a region containing five gene predictions.

investigation.

In summary, gene finders agree partially or completely on the presence of a gene in the vast majority of cases. While gene finders generally agree on the presence of a gene, they tend to disagree on the underlying gene model more often than they agree, except in the case of DC1 and Tsth20. This is likely due to only including two gene finders in their analysis rather than three, resulting in fewer opportunities for disagreement. This observation is true when applied to the start and stop positions of the gene, but further investigation and comparison of intronic and exonic sequences between genes may provide more insight. Finally, regions identified in this analysis do not always fit the ideal scenario of one gene prediction from each tool per region. Regions in which there are more than three gene predictions were observed in all assemblies included in this work. In addition, gene finders do not always predict genes on the same strand as other gene finders.

5.8 Genes in Regions of Anomalous GC Content

Figure 5.9 shows the results of applying the same region finding process from earlier to segments of the genome identified as AT-rich. AT-rich is defined as a region of genomic sequence with percent GC composition less than 28%. In comparison to results from section 5.7, we see that overall there are far fewer regions with gene predictions in AT-rich genomic segments. In DC1, Tsth20, there are very few regions with full support from both Braker2 and GeneMark, but more singletons. Again, as in section 5.7, there are no regions with partial support as only two gene finding tools were applied to those assemblies. *T. reesei* and *T. harzianum* report more regions in AT-rich genomic sequence than the other assemblies, but with the majority of regions belonging to the singleton category. *T. vires* is an interesting case, reporting a similar numbers of regions and genes in AT-rich genomic sequence as DC1 and Tsth20. *T. vires* is also the only assembly to report zero singleton gene predictions. Why *T. vires* differs from the other RefSeq assemblies is unclear. In

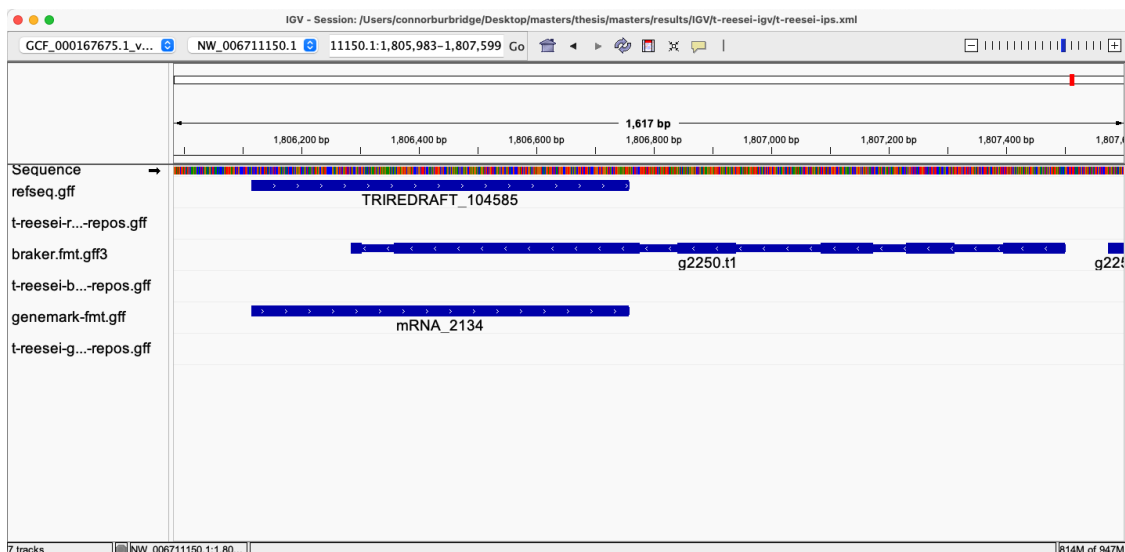


Figure 5.7: An IGV screenshot of *T. reesei* showing a region which contains gene predictions on opposite strands.

Assembly	Full Support	Partial Support	Singletons	No. Genes
DC1	11	N/A	20	42
Tsth20	2	N/A	9	13
<i>T. reesei</i>	25	18	54	194
<i>T. harzianum</i>	26	43	68	265
<i>T. virens</i>	8	11	0	49

Table 5.9: Total regions identified each assembly followed by counts of regions (both agreement and singletons) in regions of anomalous GC content.

general, there are few regions with gene predictions in AT-rich genomic segments, and within these regions, the majority of cases are isolated singleton gene predictions. These observations differ greatly from those made in nucleotide composition agnostic approach in section ??

In addition to a breakdown of regions in AT-rich genomic sequence, understanding which gene finders predict more or fewer genes in these regions may be of interest. Table 5.10 shows the number of genes predicted by each gene finding tool in regions of AT-rich genomic sequence. GeneMark appears to predict the fewest genes in AT-rich regions, while RefSeq appears to predict the most. Braker2 lies somewhere in the middle. Again, *T. virens* appears as an odd case, with very few predictions from all gene finders. Why *T. virens* differs from the other RefSeq assemblies is unclear.

Finally, to test the probability of any given gene prediction falling in an AT-rich genomic sequence, a two-sided binomial test was performed to determine if the number of genes predicted in AT-rich sequences is proportional to fraction of genomic sequence they comprise. The results of the test are shown in table

Assembly	Braker2	GeneMark	RefSeq
DC1	31	11	N/A
Tsth20	11	2	N/A
<i>T. reesei</i>	39	48	107
<i>T. harzianum</i>	81	30	154
<i>T. virens</i>	21	8	20

Table 5.10: Number of genes predicted by Braker2, GeneMark and RefSeq in AT-rich genomic sequence from each assembly.

Tool	DC1	Tsth20	<i>T. reesei</i>	<i>T. harzianum</i>	<i>T. virens</i>
Braker2	9.56^{-181}	1.14^{-259}	2.68^{-96}	4.05^{-140}	1.35^{-35}
GeneMark	5.12^{-216}	0.0	5.66^{-49}	5.37^{-219}	5.31^{-35}
RefSeq	N/A	N/A	1.29^{-49}	2.44^{-205}	7.40^{-33}

Table 5.11: p values produced from a two-sided binomial test for each combination of tool and assembly.

5.11. In all cases, it appears that the gene finding tools selected for this analysis do not predict the same proportion of genes in AT-rich genomic sequence as in typical genomic sequence.

In summary, very few regions with gene predictions are present in AT-rich genomic sequence. Additionally, genes predicted in these regions tend to be isolated and not supported by other gene finders, although some agreement is observed. In terms of number of genes predicted, RefSeq tends to predict the most genes in these AT-rich regions while GeneMark predicts the fewest. Lastly, the selected gene finding tools do not predict genes in AT-rich sequences in proportion to the fraction of genomic sequence they comprise.

5.9 InterProScan as Supporting Evidence for Predicted Genes

Pfam hits from InterProScan analysis are presented in table 5.12, from which we can identify one major trend. In general, roughly 73-76% of proteins predicted by Braker2, GeneMark and RefSeq contain a match to a Pfam entry, except in the case of *T. harzianum*, which reports a considerably lower proportion of genes with Pfam matches. Why the proportion of RefSeq proteins with Pfam matches in *T. harzianum* is so low is unknown. This is promising performance for the gene finders as the RefSeq annotations demonstrate similar proportions of Pfam hits to predicted proteins. The total counts may be deceiving however, as predictions from Braker2 may result in more than one protein product per gene, whereas in the case of GeneMark, only one protein is produced per gene model. From visual inspection of Pfam hits mapped back to the references,

it appears that in general, when gene finders agree that a gene is present, InterProScan reports the same Pfam match in all three predictions. An example of agreement between Braker2, GeneMark, RefSeq and InterProScan is shown in figure 5.8. It is important to note that the position of the Pfam match in IGV does not indicate the true position of the Pfam match in the gene, but provides an indication of the presence of Pfam matches. Pfam matches are offset from the start of the gene based on the start and end position of the Pfam match in the protein sequence. For example, if a Pfam match has a start position 10 amino acids into the protein sequence, the corresponding start position in the resulting GFF is 10bp downstream from the start of the gene.

Assembly	Braker2	GeneMark	RefSeq
DC1	$100 \times (\frac{10676}{14479}) = 73.73\%$	$100 \times (\frac{8416}{11354}) = 74.12\%$	N/A
Tsth20	$100 \times (\frac{11389}{15546}) = 73.26\%$	$100 \times (\frac{9168}{12373}) = 74.10\%$	N/A
<i>T. reesei</i>	$100 \times (\frac{8471}{11704}) = 72.38\%$	$100 \times (\frac{6990}{9196}) = 76.01\%$	$100 \times (\frac{6964}{9111}) = 76.44\%$
<i>T. harzianum</i>	$100 \times (\frac{11370}{15408}) = 73.79\%$	$100 \times (\frac{9061}{12164}) = 74.49\%$	$100 \times (\frac{9293}{14065}) = 66.07\%$
<i>T. virens</i>	$100 \times (\frac{11249}{15062}) = 74.68\%$	$100 \times (\frac{8871}{11866}) = 74.76\%$	$100 \times (\frac{9062}{12383}) = 73.18\%$

Table 5.12: Table with counts of predicted genes with Pfam annotations from InterProScan

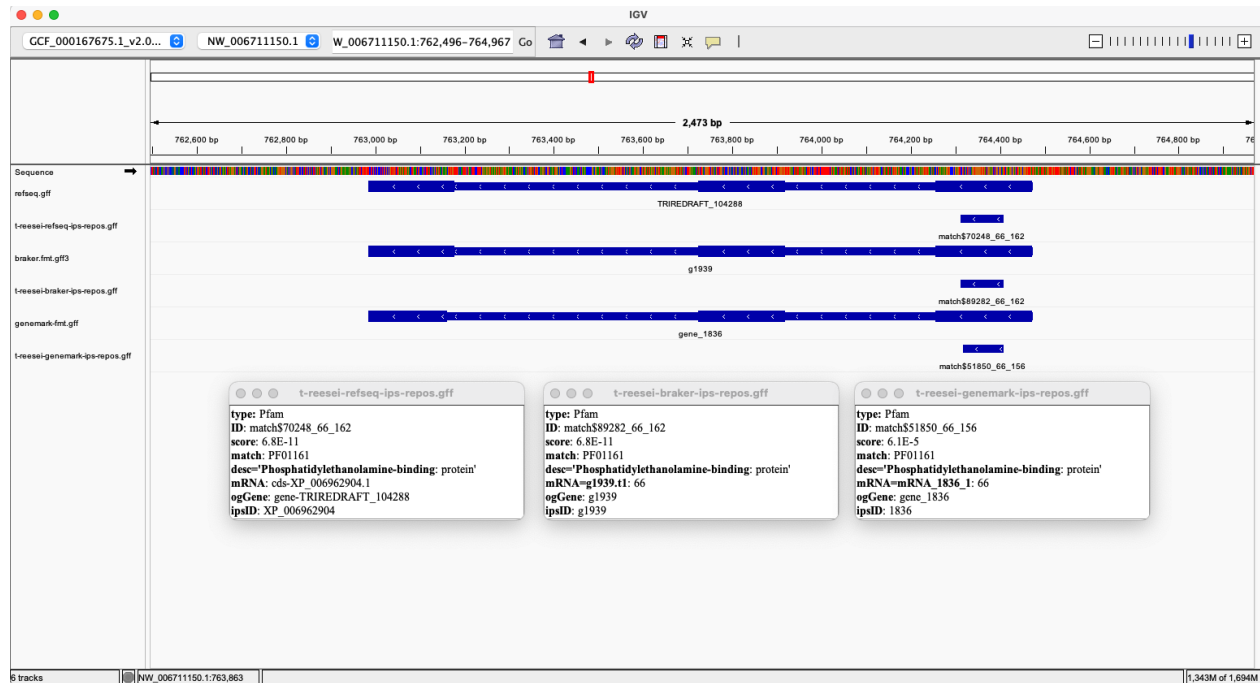


Figure 5.8: An IGV capture showing complete agreement between gene finders for both gene model and protein Pfam hits

While cases of complete agreement are abundant, cases of disagreement also exist and in strange forms. In many cases, while the gene finders agree on the presence of a gene, only the RefSeq protein product contains a match to the Pfam database. Why this may be the case is unclear, and may warrant further investigation.

There are also many cases in which InterProScan reports the same Pfam hits for individual proteins, but the gene models in the region do not agree. There are even cases such as the region shown in figure 5.9, where Braker2 and GeneMark agree that two genes and their associated proteins and Pfam matches are separate, but RefSeq only reports one gene with multiple Pfam hits. There are also several cases where two tools are in agreement with proteins containing Pfam hits while another is not. Even more interesting are cases such as the one shown in figure 5.10, in which Braker and GeneMark predictions contain Pfam matches while RefSeq does not report a gene at all. This may be due to experimental data used in the RefSeq training process or a result of curation. Regardless of the tool, these cases demonstrate well that gene finders are not always in agreement, to the point that predictions are not present even though protein products from other gene finders contain known Pfam matches.

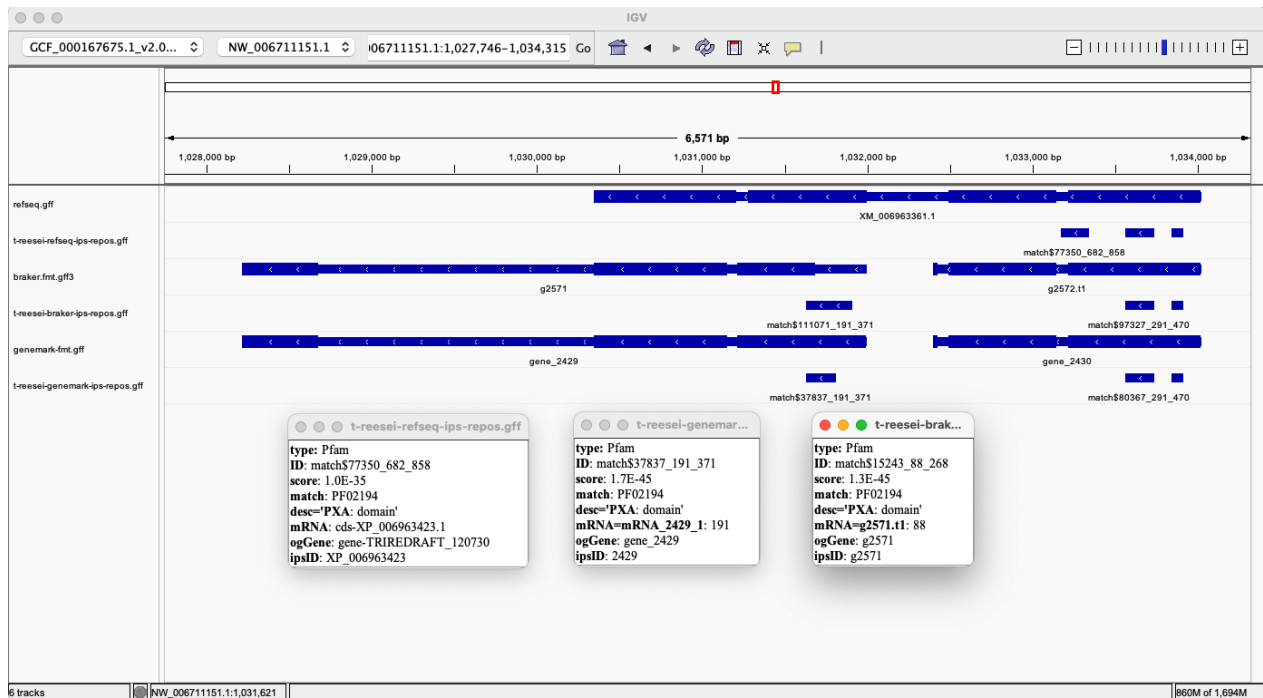


Figure 5.9: An IGV capture showing Braker2 and GeneMark reporting two genes and their resulting proteins and Pfam hits as separate, while RefSeq reports one gene, one protein and three Pfam matches.

In summary, the protein products from Braker2 and GeneMark predictions do contain matches to the Pfam database. The proportions of matches to total proteins are similar to that of the RefSeq annotation, sitting between 65 and 75 percent. While Pfam hits to Braker2, GeneMark and RefSeq proteins generally agree, we do observe regions in which there is disagreement in several forms.

5.10 Selection of Gene Finding Tool

With all of these results, it makes sense to explore the question of which gene finding tool one should choose for optimal gene prediction performance. Results from this work are summarized in table 5.13.

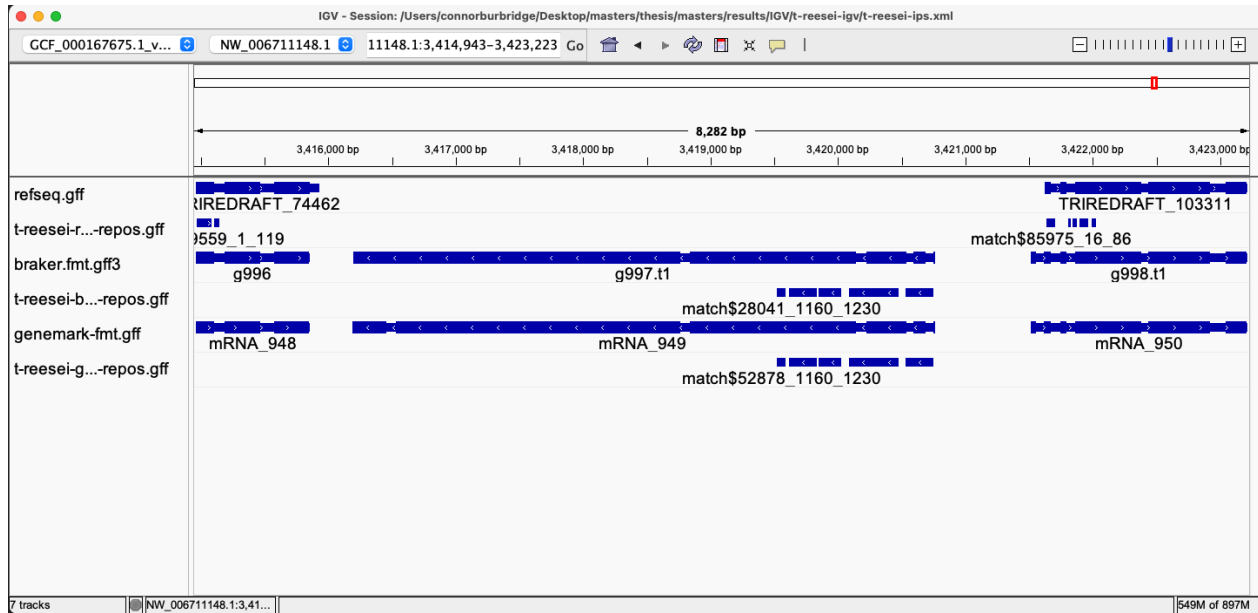


Figure 5.10: An IGV capture showing a scenario where GeneMark and Braker2 agree on a gene model with supporting Pfam evidence and RefSeq does not report any gene.

Ignoring availability and use of the gene finding tools, it would appear that RefSeq performs the best in the remaining categories, earning top marks in every category except in it's ability to predict very short genes. Braker2 earns second place, however this does not capture Braker2's failure in predicting accurate numbers of genes in DC1, Tsth20, *T. harzianum* and *T. virens*. GeneMark comes in last, excelling only in number of genes predicted and Pfam support for the genes that it predicts.

Relating these observations to use-case scenarios; in the case that your organism of interest has a RefSeq annotation associated with it, the RefSeq gene prediction process appears to produce the best set of predictions. If users also have experimental evidence, such as RNAseq data under experimental conditions, it may be worthwhile training a Braker2 model and predicting genes with Braker2 to supplement the already well performing RefSeq gene predictions. If the organism of interest is not a RefSeq individual but training data is available, Braker2 is the next best option, although it is important to note that the application of a trained Braker2 prediction model to an organism from which the training data did not originate is not advised based on the results presented in this work. While it is true that the *T. reesei* genome differs from other *Trichoderma* genomes, it's status as a representative RefSeq organism makes it a somewhat of a gold standard. In this case, applying a gene model trained using evidence from the gold standard produces biased numbers of genes predicted in other *Trichoderma* genomes. While Braker2 technically scores the second highest, users must be very careful when selecting training data, and ensure that the training data either comes from the organism of interest, or comes from a very closely related organism with a highly similar genome. In the case that no appropriate training data is available, GeneMark is still an option, and users can be confident that the tool predicts a reasonably accurate number of genes with supporting Pfam matches. It is also important to note that GeneMark does not perform as well in AT-rich regions as Braker2 and RefSeq, does not predict

Category	Braker2	GeneMark	RefSeq
Availability	3	3	0
Ease of install	1	2	0
Ease of use	3	3	0
# of genes predicted	0	3	3
# of transcripts predicted	3	0	2
Predicts shortest genes	2	1	0
Predicts more shorter genes	1	0	3
BUSCO Performance	2	1	3
Performance in AT-rich sequence	2	1	3
Predictions with InterProScan support	3	3	3
Final Score (Publicly Available)	20	17	N/A
Final Score (Ignoring Availability)	13	9	17

Table 5.13: Table with scores attributed to performance of each gene finder in several categories. The score definitions for performance are as follows: 0 - fail, 1 - pass, 2 - good, 3-excellent. Since RefSeq is not publicly available, it is marked as N/A in the publicly available final scores.

isoforms, and systematically fails to predict some BUSCO orthologs.

When availability of a gene finding tool becomes a concern and RefSeq is not considered, the scores change significantly, but Braker2 still outperforms GeneMark. If the organism of interest is not considered a representative RefSeq individual, but supporting evidence specific to that organism or a very closely related organism is available, a trained Braker2 prediction model will perform well. Again, in the case that the organism is not a RefSeq individual and no appropriate training data is available, GeneMark is still a reasonable option even with the previously identified caveats.

In summary, these results indicate that if your organism is a RefSeq organism, use the RefSeq annotation. If no RefSeq predictions are available but appropriate training data is, one should use Braker2. If the training data is of questionable similarity or not available at all, users can fall back on *ab initio* gene finders such as GeneMark, which while not ideal, still predict genes with supporting evidence.

5.11 Conclusions

References

- [1] Jill Adams. Complex Genomes: Shotgun Sequencing. *Nature Education*, 1(1):186, 2008.
- [2] Tomáš Brůna, Katharina J Hoff, Alexandre Lomsadze, Mario Stanke, and Mark Borodovsky. BRAKER2: automatic eukaryotic genome annotation with GeneMark-EP+ and AUGUSTUS supported by a protein database. *NAR genomics and bioinformatics*, 3(1):lqaa108, mar 2021.
- [3] Phillip E C Compeau, Pavel A Pevzner, and Glenn Tesler. How to apply de Bruijn graphs to genome assembly. *Nature biotechnology*, 29(11):987–991, nov 2011.
- [4] Girum Fitihamlak Ejigu and Jaehee Jung. Review on the Computational Genome Annotation of Sequences Obtained by Next-Generation Sequencing. *Biology*, 9(9), sep 2020.
- [5] Sara Goodwin, John D McPherson, and W Richard McCombie. Coming of age: ten years of next-generation sequencing technologies. *Nature Reviews Genetics*, 17(6):333–351, 2016.
- [6] Christian P Kubicek, Andrei S Steindorff, Komal Chenthamara, Gelsomina Manganiello, Bernard Henrissat, Jian Zhang, Feng Cai, Alexey G Kopchinskiy, Eva M Kubicek, Alan Kuo, Riccardo Baroncelli, Sabrina Sarrocco, Eliane Ferreira Noronha, Giovanni Vannacci, Qirong Shen, Igor V Grigoriev, and Irina S Druzhinina. Evolution and comparative genomics of the most common *Trichoderma* species. *BMC Genomics*, 20(1):485, 2019.
- [7] Alexandre Lomsadze, Vardges Ter-Hovhannisyan, Yury O Chernoff, and Mark Borodovsky. Gene identification in novel eukaryotic genomes by self-training algorithm. *Nucleic Acids Research*, 33(20):6494–6506, 2005.
- [8] Mosè Manni, Matthew R Berkeley, Mathieu Seppey, Felipe A Simão, and Evgeny M Zdobnov. BUSCO Update: Novel and Streamlined Workflows along with Broader and Deeper Phylogenetic Coverage for Scoring of Eukaryotic, Prokaryotic, and Viral Genomes. *Molecular Biology and Evolution*, 38(10):4647–4654, 2021.
- [9] Vivien Marx. Method of the year: long-read sequencing. *Nature Methods*, 20(1):6–11, 2023.
- [10] Niranjana Nagarajan and Mihai Pop. Sequence assembly demystified. *Nature Reviews Genetics*, 14(3):157–167, 2013.
- [11] NCBI. NCBI Eukaryotic Annotation Pipeline, 2024.
- [12] Miroslav Plohl, Nevenka Meštrović, and Brankica Mravinac. Centromere identity from the DNA point of view. *Chromosoma*, 123(4):313–325, aug 2014.
- [13] Biancamaria Senizza, Fabrizio Araniti, Simon Lewin, Sonja Wende, Steffen Kolb, and Luigi Lucini. *Trichoderma* spp.-mediated mitigation of heat, drought, and their combination on the *Arabidopsis thaliana* holobiont: a metabolomics and metabarcoding approach. *Frontiers in Plant Science*, 14, 2023.
- [14] R Keith Slotkin. The case for not masking away repetitive DNA. *Mobile DNA*, 9(1):15, 2018.
- [15] Ioannis S Arvanitoyannis Theodoros H. Varzakas and Haralambos Baltas. The Politics and Science Behind GMO Acceptance. *Critical Reviews in Food Science and Nutrition*, 47(4):335–361, 2007.
- [16] Todd J Treangen and Steven L Salzberg. Repetitive DNA and next-generation sequencing: computational challenges and solutions. *Nature reviews. Genetics*, 13(1):36–46, nov 2011.

- [17] David J Winter, Austen R D Ganley, Carolyn A Young, Ivan Liachko, Christopher L Schardl, Pierre-Yves Dupont, Daniel Berry, Arvina Ram, Barry Scott, and Murray P Cox. Repeat elements organise 3D genome structure and mediate transcription in the filamentous fungus *Epichloë festucae*. *PLOS Genetics*, 14(10):1–29, 2018.
- [18] Sheridan L Woo, Rosa Hermosa, Matteo Lorito, and Enrique Monte. Trichoderma: a multipurpose, plant-beneficial microorganism for eco-sustainable agriculture. *Nature Reviews Microbiology*, 21(5):312–326, 2023.