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Bovine Genome Database: Tools for Mining the *Bos taurus* Genome

Running Title: Bovine Genome Database

Darren E. Hagen¹, Deepak R. Unni¹, Aditi Tayal¹, Gregory W. Burns¹, Christine G. Elsik^{1,2,3*}

Affiliation:

1. Division of Animal Sciences, University of Missouri, Columbia, MO USA
2. Division of Plant Sciences, University of Missouri, Columbia, MO, USA
3. MU Informatics Institute, University of Missouri, Columbia, MO, USA

*Corresponding Author:

Christine G. Elsik
Division of Animal Sciences, Division of Plant Sciences, MU Informatics Institute
University of Missouri
920 East Campus Drive
Columbia, Missouri 65211 USA
elsikc@missouri.edu

Abstract

The Bovine Genome Database (BGD; <http://bovinegenome.org>) is a web-accessible resource that supports bovine genomics research by providing genome annotation and data mining tools. BovineMine is a tool within BGD that integrates BGD data, including the genome, genes, pre-computed gene expression levels and variant consequences, with external data sources that include quantitative trait loci (QTL), orthologues, Gene Ontology, gene interactions and pathways. BovineMine enables researchers without programming skills to create custom integrated datasets for use in downstream analyses. This chapter describes how to enhance a bovine genomics project using the Bovine Genome Database, with data mining examples demonstrating BovineMine.

Key words

Bovine, cattle, *Bos taurus*, genome database, genome annotation, orthology, pathway, gene expression, single nucleotide polymorphism, data mining, InterMine, BovineMine

1. Introduction

The goal of the Bovine Genome Database (<http://bovinegenome.org>) is to support the efforts of bovine genomics researchers by providing easy access to the bovine reference genome assembly and annotations of genome features via a graphical genome browser, sequence database searching, data mining, and bulk data download [1]. Data provided by BGD includes annotation data gathered from external sources as well as computed data to improve genome annotation. BGD provides tools for manual annotation, viewing multiple genome assemblies, and exploring a tissue-specific gene expression atlas for both RefSeq and Ensembl genes. In addition, BGD

hosts a data mining warehouse, BovineMine, which integrates tissue-specific gene expression levels, QTL and external sources of functional annotation, such as pathways and interactions, for fine-scale data mining and generation of custom data sets. BGD includes both the Ensembl and RefSeq gene sets, and provides database cross reference tools to seamlessly convert from one to the other.

2. Methods

2.1 Website Navigation

The navigation bar of Bovine Genome Database provides access to all of the web-based informatics tools, which include data mining (BovineMine), BLAST searching, genome browsing (JBrowse), manual gene annotation (Apollo), various quick lookup tools and data download. Since the bovine reference genome has been revised several times, an “Assembly History” page provides information about previous and current reference genome assemblies to mitigate confusion.

2.2 BGD Lookup Tools

The Lookup Tools tab in the BGD navigation bar provides access to quick lookup tools to perform chromosome or gene identifier conversion or select RNA-seq JBrowse tracks that provide expression information for specific genes (Fig.1A). These tools are actually very simple search interfaces that submit queries to BovineMine (described below) for quick lookups of single identifiers. BovineMine is recommended for more complex queries or searching a list of ids. The Lookup Tools will change depending on needs associated with specific reference

genome assemblies. For example, the current Annotation Assembly Tool, which provides locations of genes (Ensembl, RefSeq, OGSv2) on two bovine assemblies (UMD3.1 and Btau_4.6.1) will be updated upon the release of a new bovine reference genome assembly.

2.3 JBrowse, Apollo and the Faceted Track Selector

Genome browsing is provided using JBrowse [2] as implemented by Apollo [3]. From a user-perspective, the only differences between BGD JBrowse and BGD Apollo are the gene editing functions and the user annotation pane that are available only when logged into Apollo. The evidence tracks are identical across the browsers. All BGD users can access JBrowse, while only users registered for annotation can access Apollo. An Apollo registration link is provided in the navigation bar. An Apollo user guide and demo are available at the Apollo website (<http://genomearchitect.org>). The remainder of this section will focus on BGD specific data and browser features. BGD JBrowse includes over 300 “tracks”, so BGD implements a faceted track selector (Figs 1B and 1C) that is available by clicking the “Select Tracks” tab in the upper left corner of the browser (Fig.1D). The track selector organizes tracks into the following data types: Gene Prediction, LiftOver Gene Prediction, Genome Assembly Gaps, Alternate Assembly Alignment, Protein Homolog Alignment, Microarray Probe Alignment, Variation, QTL Region, Repeat, Combined Cufflinks, and five different RNA-seq data types.

The Gene Prediction tracks are organized according to source database (e.g. RefSeq or Ensembl) and the gene type assigned by the source database (e.g. protein-coding, several non-coding gene types, pseudogenes, gene models with errors due to assembly issues). The RefSeq tracks also include gene models based on the *ab initio* Gnomon pipeline, and a track called “ambiguous

genes”, which are gene loci that code both protein-coding and noncoding transcripts. If a particular RefSeq gene or transcript is not found in the expected track (e.g. RefSeq protein coding), you should view the “ambiguous genes” and “frameshift genes” tracks. LiftOver Gene Prediction tracks include genes that were predicted based on a previous or alternate assembly version, and are actually alignment tracks rather than gene models. Genes in the LiftOver tracks may have errors, such as missing exons, frameshifts and internal stop codons. Any gene in a LiftOver track may exist at multiple chromosome coordinates.

In addition to data type categories, RNA-seq tracks are organized according to both Organ System, from the Mouse Anatomy Ontology [4] and the Uberon Anatomy Ontology [5], and Brenda Tissue Ontology [6]. After highlighting one or more data types, organ systems or tissues in the left panel, only tracks under those categories appear in the table in the right panel. Tracks can be further filtered using a text search in the “Contains Text” box for any information found in the table, which includes data type and track name for all tracks, Brenda Tissue Ontology Name, Brenda Tissue Ontology All Levels, Organ System, Sex, Age, Individual, Sample Name and SRA Run Accession for RNA-seq tracks.

Each RNA-seq dataset is available in 6 different track configurations, which can also be filtered with the faceted track selector. The RNA-seq HeatMap and XY-Plot tracks are useful for zoomed-out views of the chromosome, to see areas with high expression levels. The other RNA-seq tracks are more suitable for zoomed-in views used to compare transcript isoforms with RNA-seq alignments. The Cufflinks tracks contain assembled contigs, and show up as either histograms depicting feature density when zoomed out, or gene models depicting exon/intron

structure when zoomed in sufficiently. The Junctions tracks show arcs connecting parts of spliced reads; these are useful for quickly visualizing discrepancies in exon/intron structure or split/merge gene model disagreements when viewed along with a gene prediction tracks (Fig.1D). The BAM tracks require a sufficient zoom-in level. The Collapsed BAM track is the less compute intensive of the two BAM tracks, and shows individual read alignments and spans within spliced read alignments (Fig.1D). The Draggable BAM tracks are the most compute intensive, and require the highest zoom level. This track allows annotators to drag single reads to the Apollo annotation panel, but does not provide advantages over the Collapsible BAM track when simply viewing in JBrowse.

Once suitable tracks are identified, they are selected by clicking the corresponding box on the left side of the table. Clicking “Back to Browser” above the left side of the table hides the track selector. Within the browser, tracks can be rearranged by dragging the track label.

2.4 BLAST

The BGD BLAST search interface leverages the SequenceServer platform [7]. When the search database is a genome assembly, BLAST hits are linked to JBrowse based on match coordinates. When the search database is coding sequence, transcript or peptide, BLAST hits are linked to a JBrowse location based on the hit identifier. SequenceServer also provides downloadable tab-delimited or BLAST XML reports and graphical overviews of the matches.

2.5. BovineMine

BovineMine is a powerful data mining tool that allows scientists with limited programming skills to exhaustively explore the bovine genome and associated biological data from a variety of external sources. BovineMine, which is accessible from the BGD navigation bar, employs the InterMine data warehousing system [8] to integrate the data and allow you to generate customized data sets. The data currently available in BovineMine include reference genome assemblies, genes, proteins, protein families and domains, orthologs and homologs, biochemical pathways, interactions, Gene Ontology annotations, cattle quantitative trait loci (QTL), variation, and publications (Table 1). BGD-specific data, including computed variant effects and RNA-seq-based gene expression data, permits you to mine tissue specific gene expression levels in the context of genomic variation data. In addition to the bovine reference genome assembly, BovineMine includes the reference genome assemblies and gene sets of sheep and goat to allow researchers of non-bovine ruminants to leverage the extensive amount of available bovine genomics data.

2.5.1 BovineMine Navigation Bar and Homepage

The BovineMine navigation bar is available on all BovineMine pages (Fig.2). Tabs in the navigation bar direct you to the relevant entry points for different analysis types, and also include information about the data sources (Data Sources) and a diagram depicting data integration (Data Model). The Help tab opens a new browser window with a written tutorial and short videos demonstrating BovineMine features.

The Quick Search and Quick List tools on the BovineMine homepage (Fig.2) allow you to quickly search the database for a single keyword (Quick Search, more in Subheading 2.5.3) or a

list of identifiers (Quick List, more in Subheading 2.5.5). Halfway down the home page is a set of tabs that provide access to predefined template queries organized into categories (GENE, EXPRESSION, PROTEINS, FUNCTION, HOMOLOGY, INTERACTIONS, VARIATION, ALIAS AND DBXREF, ENTIRE GENE SET). The ENTIRE GENE SET category lists templates for querying entire gene sets, such as retrieving all microRNA for a given organism. The ALIAS AND DBXREF category provides templates that convert identifiers between gene sets, allowing you to relate gene identifiers between the Ensembl and RefSeq gene sets. Upon the release of an updated bovine reference genome, template queries will be added to relate gene identifiers between the old and new gene sets. Subheading 2.5.7 provides further details regarding template queries.

2.5.2 MyMine

Although you may use BovineMine anonymously, creating a MyMine account provides several advantages. While logged in to MyMine, your query history is automatically saved and you can save lists, queries and template queries for use during later sessions. Your work is maintained even in the case of accidental server disconnection. You can also organize your lists with tags and share them with other MyMine users by selecting the “Share with users” link. You can register or log in by either choosing the “Log In” link in the header or by choosing the red MyMine tab in the navigation bar. Registration requires only an email address to be entered in the “Username” area and setting a password.

2.5.3 Quick Search

You can input keywords for text searching in two areas, the Quick Search box on the BovineMine homepage and the keyword search box below the navigation bar on all BovineMine pages. Since Quick Search is a full text search, you can enter any kind of identifier or text string, including the wildcard '*'. For example, after entering the gene symbol IGF2 into the Quick Search box and clicking "Search", you will see a page summarizing the query, and over 700 results for which IGF2 is included in the text (Fig.3). You can filter results by clicking a data category or organism name within the box on the left of the page (Fig.3). Details are provided about each result, including a score indicating the similarity of your query to the result. Clicking an individual result provides the report page for that object.

2.5.4 Report Page

BovineMine generates a report page with detailed information customized by data class (e.g. genes, transcripts, proteins, variants) for each data object. Every report page is a collection of tables, each of which can be sorted, filtered and exported. The gene report page is subdivided into sections including Summary, Transcripts, Protein, Function, Homology, Interactions, Publication, and Other. The Summary information includes the gene identifier, gene symbol, description, chromosomal location, strand information, and other identifiers. The Transcript section lists transcript identifiers, each of which is linked to a transcript report page that includes a table of expression values based on alignment of Illumina RNA-seq data from tissues of L1 Dominette 01449, as well as SRA metadata. The Transcript section of the Gene report includes graphical views of the transcripts; clicking a transcript graphic opens BGD JBrowse and allows you to view the transcripts in genomic context, along with other JBrowse tracks (Subheading 2.3). The Transcript section also allows you to download fasta-formatted sequences. The

Proteins section lists protein identifiers that link to Protein report pages with information such as protein family, GO annotations, InterPro domains, and curated notes from UniProt. The Function section of the Gene report provides GO annotations with evidence codes. The Homology section lists mammalian homologs.

2.5.5 List Tool

The List Tool allows you to create unique datasets based on lists of identifiers. As opposed to the Quick Search function, which returns any report page containing the provided keyword, the List Tool performs a database lookup to return objects based on their primary identifiers, which include gene ids or symbols, transcript ids, and protein ids. Two list functions are available, the Quick List tool found on the BovineMine homepage and the full List Tool, available via the Lists tab in the BovineMine navigation bar. The Quick List tool is a streamlined version of the List Tool, and can be used by manually entering gene or protein identifiers separated by commas, spaces, tabs or line breaks.

The advanced-function List Tool allows you to choose from among a larger array of data types, select a species, and enter a list either manually or by choosing a file to upload (Fig.4A). Clicking Lists in the navigation bar will lead you to an Upload page or the list View page. You can toggle between the two pages using “Upload” or “View” in the black bar below the BovineMine navigation bar. List analysis begins by clicking the “Create List” button using the main List Tool Upload page or “Analyze” using Quick List. BovineMine then performs a lookup and returns an intermediate page (Fig.4B) prompting you to name the list and possibly to provide further input to select from among duplicate identifiers from different data sets. Once

you click “Save a list of X Genes” (where X is a number), your list is saved for the duration of your session if you are not logged in, or permanently if you are logged in to MyMine. The resulting page provides your list in a table form with other relevant information (Fig.4C). The “Save as List” drop-down menu allows you to re-save the list if you forgot to name it before, or to select different columns in the table to save. Your saved lists can be used in BovineMine queries (Subheadings 2.5.7 and 2.5.8). The list analysis page also contains enrichment widgets that operate on gene lists. Enrichment widgets are described further in Subheading 2.5.6.

The List View page shows user-saved lists highlighted in purple and premade BovineMine lists with a white background. The View page also includes set operation functions. Finding the difference, union or intersection between two or more saved lists leads to the creation of a new list (Fig.5).

An advantage of the List Tool is that it enables you to remove redundancy in a list, or determine the source of an identifier. Identifiers submitted to the list function may include any combination of ids or symbols, and will return results as long as they are found in BovineMine and are of the selected data type. For example, 515523 (RefSeq gene id), BTG1 (gene symbol), and ENSBTAG0000006858 (Ensembl gene id) each return a result when the “Gene” data type is selected. Thus, the List Tool allows you to perform meta-analyses of published studies without requiring you to have *a priori* knowledge of the data source. Entering the gene ids and symbols given above, choosing “Gene” and “B. taurus” from the respective pull-down menus, and clicking “Create List” returns results for these genes in cattle. A green button allowing you to “Save a list of 2 Genes” suggests the results need manual inspection as we submitted a list of

three genes. In this instance, the gene symbol BTG1 produced multiple records, one each for the RefSeq and Ensembl gene ids associated with BTG1, so BTG1 is not included in the count of two genes. You are asked to choose which record to include in the list by clicking the “Add” button to the right of the record or the “Add All” button in the upper right corner of the “Duplicates” section. After making a choice, RefSeq gene in this example, you have the option to name the list before finally saving the list by clicking “Save a List of 3 Genes”. This takes you to the List Analysis Page, which includes a table listing the three genes.

2.5.6 Enrichment Widgets

The BovineMine List tool analyzes each list of genes for enrichment of gene ontology, pathways, and publications, and presents the data using widgets (Fig.6). Options to select test correction, p-value and background population are given for each widget. For gene enrichment analysis, the default background data set is all genes in the organism that have annotations of the type being calculated. Since BovineMine may include several gene sets for a single organism, (ex: RefSeq, Ensembl, OGS), it is recommended that you change the background population to a gene set appropriate for your subject gene list. Premade gene lists are provided for each gene set in BovineMine, and can be selected within an enrichment widget by clicking the “Change” button (Fig.6). The List Tool also makes it easy to create more refined background gene lists for specific questions. For example, you can create lists of all expressed genes to use as the background to test for enrichment in differentially expressed genes.

Analysis of Differentially Expressed Genes Using List Enrichment Widgets: This example demonstrates use of the BovineMine List tool for enrichment analysis in a differential gene

expression study. We will use a dataset of differentially expressed genes between chorionic tissue extracted 34 days after artificial insemination (AI) and extra embryonic tissue 18 days post AI from the study reported by Biase *et al.* [9]. Download the file, Dataset_S01, using this link: <http://www.pnas.org/content/suppl/2016/12/08/1520945114.DCSupplemental/pnas.1520945114.sd01.xlsx>

1. The first step is to create a gene list that will serve as a background gene list in enrichment analysis. In this case, we will use all expressed genes. Click the List tab. Choose “Gene” from the “Select Type” pull-down menu and “B. taurus” from the “Organism” menu.
2. Select all Gene ids from column B of the spreadsheet and paste them into the List Tool text box. You might have noticed that the gene ids included ids from both Ensembl and NCBI. There is no need to separate them. It appears that Ensembl ids were the main source of ids in this study, and RefSeq ids were used when an Ensembl id did not exist for a particular gene. Click “Create List”.
3. In the resulting page you will notice that 10,923 out of 10,963 identifiers were found in BovineMine. The missing genes are listed at the bottom of the page. These Ensembl ids are missing because the published study used an older Ensembl gene set, and some of the genes have been removed from the newer Ensembl gene set.
4. To save your entered gene list, enter the name “Background Gene List” into the text box under “Choose a name for the list” and click the green “Save a list of 10923 Genes” button. An advantage of the BovineMine enrichment tool is that you were able to create the appropriate background gene list even though your data contains identifiers from different gene sets.

5. After saving the list, a new table of genes will appear. Notice that an enrichment analysis has automatically been performed and appears below the table. However, this is not the analysis you care about. This analysis compared your background list of all expressed genes to the default background list of all bovine genes in BovineMine. It is not recommended that you ever use the default background list in BovineMine, because BovineMine contains multiple gene sets, causing the default background list to be redundant.
6. The next step is to create the test gene list and perform an enrichment analysis with the List Tool. Click the List Tool tab and in the text box, paste only the gene ids found in column B from Dataset_S01 with an FDR <0.05 (rows 4-4617). And click “Create List” (Fig.4A).
7. Name the new list “DE Gene List” and click the green “Save a list of 4595 Genes” (Fig.4B)
8. After saving the list you are taken to the List Analysis page, with a table that can be manipulated using the column management tools (Fig.4C).
9. Further down the page you will find widgets for enrichment analysis for publications, gene ontology, and pathways as well as links to orthologs in other species. For each enrichment widget, click the “Change” button for Background population and select “Background Gene List”, which is the list you saved in step 4. The enrichment analysis will be rerun with the proper background data set (Fig.6).

2.5.7 Template Queries

Beyond the simple search, you can query BovineMine using predefined template queries, available by clicking either the Templates tab in the navigation bar or one of the Template category tabs in the middle of the BovineMine home page. Clicking a template query name takes you to an interface that may be pre-populated with examples and usually requires your input. For example, choosing the “Bovine Gene → Transcripts → Expression” template under the EXPRESSION category produces a web form with up to five fields for your input (Fig.7), with the Tissue field being optional. In most cases you would modify the input identifier and enter a cutoff in one of the expression level fields. You can click “Show Results” button to run the query or click “Edit Query” to go to the QueryBuilder (described in Subheading 2.5.8) to modify the query by adding or removing search constraints or selecting additional information to be included in the output.

Template Query Example: Suppose you are interested in the gene Ago2, a key player of RNAi-dependent gene silencing. You would like to know in which tissues Ago2 is expressed, in order to make an informed decision about which tissues to focus on. Since BovineMine includes tissue levels computed on RNA-seq data of over 90 tissues from the reference genome individual, L1 Dominette 01449, you could use a simple template query to identify tissues with Ago2 expression.

1. Click the “Templates” tab in the toolbar at the top of the BovineMine webpage and select the template, “Bovine Gene → Transcripts → Expression” (Fig.7).
2. In the Gene field, you could enter “Ago2”, the NCBI gene id “404130” or the ENSEMBL gene id “ENSBTAG00000001579”. Note that if you enter a gene symbol, you may retrieve the gene from more than one gene set. For this example, we will use the NCBI gene id “404130”.
3. Leave the tissue filter off so the results table will include information for all tissues.
4. Select “>=” from the pull-down menu and enter “10” in the FPKM section.
5. Click “Show Results”

This example returns a table with four rows, each showing a tissue for which Ago2 is expressed with an FPKM of ten or greater (Fig.7). These results would allow you to focus on muscular tissue, choroid plexus, or testis for future expression studies. Furthermore, the isoform column indicates that the NCBI gene includes only one transcript isoform (NM_205794.1). In cases where the gene codes for multiple isoforms, each row would provide the expression data for an individual transcript isoform in that tissue.

2.5.8 QueryBuilder for Custom Queries

If there is no template query to fit your needs, you can use the QueryBuilder to construct your own query. Although the QueryBuilder is not intuitive and requires experimentation to gain familiarity, mastering QueryBuilder to create an integrated data set is likely to be far more efficient than learning a scripting language such as Perl or Python.

Before initiating query construction, you may wish to view the BovineMine data network diagram available by clicking the Data Model tab in the BovineMine navigation bar to visualize connections between data sources. In addition, the Identifier Relationship Table available on the Data Model page, and in Table 2 of this chapter, indicates which gene and protein identifiers can be used to retrieve different data sets. For example, Table 2 shows that to retrieve KEGG pathways for bovine genes, you need to input bovine RefSeq identifiers. If your dataset has Ensembl identifiers, you can use the “Gene ID → Database Cross Reference ID” template query to convert identifiers prior to constructing your query.

After choosing the “QueryBuilder” tab in the BovineMine navigation bar, start building a query using the pull down menu under “Select a Data Type to Begin a Query” (Fig.8A). Once you select a data type, the Model Browser opens and reveals the hierarchical structure of the BovineMine data model, beginning with the data class you selected (Fig.8B). Stemming from the main data class are its attributes, subclasses and references to other data classes. A “+” symbol next to a data class allows you to open that part of the tree to reveal attributes and subclasses. Query construction begins by selecting either SHOW or CONSTRAIN to the right of a class or attribute. Choosing CONSTRAIN generates a pop-up box that allows you to enter an identifier for which the class will be searched (Fig.8C). When you choose CONSTRAIN at the class level, any attribute of the selected class can be used as a constraint. For example, if you select CONSTRAIN next to “GENE”, either a gene id or gene symbol, both listed as GENE attributes, could be used to constrain the search. If you are logged into MyMine and have already saved a list, the pop-up box provides the additional option of selecting the list to constrain multiple searches, as long as the list is composed of the appropriate data type. For example, if you choose

to construct a query by selecting the “Gene” data class, the list provided as a constraint must be a list of gene identifiers, not transcript or protein identifiers. Choosing SHOW next to an attribute adds the attribute as an output column. The “Fields selected for output” section below the Model Browser shows blue boxes that signify output columns. You can drag the boxes to modify column order, add descriptions to columns, and indicate whether a column should be sorted using the A->Z function. You can run the query by clicking “Show results” or you can download the XML to share the query with others. While logged into your MyMine account you can save the query as a template for reuse or additional editing. The query output table can be manipulated or filtered by using the Column Manager tools (described in Subheading 2.5.10).

QueryBuilder Example: Genes underlying QTL for Residual Feed Intake: BovineMine includes curated bovine QTL data from AnimalQTLdb [10], and allows you to identify QTL for a trait of interest along with genes or other genomic features underlying the QTL regions. In this example, we will retrieve RefSeq genes underlying QTL for the trait “Residual Feed Intake” (Fig.8).

1. Click the “QueryBuilder” tab in the BovineMine navigation bar.
2. In the box titled “Select a Data Type to Begin a Query,” use the scrolling menu and select the class “QTL” (Fig.8A). This action highlights “QTL” and enables the “Select” button. Now click “Select”.
3. You are presented with a view of the Model Browser and Query Overview (Fig.8B). The Model Browser, rooted at the QTL data class, shows the attributes of QTL and data classes that are connected to QTL. Since you would like to see data for a specific trait of interest, click CONSTRAIN next to “Trait”. A pop-up box appears and you can now

enter the trait “Residual Feed Intake” (not case sensitive) and select “=” from the pull-down menu (Fig.8C). Click “Add to query”. If you are unsure of the trait nomenclature, you can use wildcards in the constraint, for example “*feed*”, and later filter for the correct trait in your output table. In order to filter, you would need to show the trait in the output. After you have clicked “Add to Query”, notice the constraint is shown in the Query Overview. The constraint can be edited by clicking the blue pencil symbol, or removed by clicking the red X.

4. Although you constrained the query for a specific trait, you should include the trait in the output to ensure you did not make an error in entering the constraint, and to keep pertinent information together in your analysis to refer back to in the future. To do so, go back to the Model Browser, and click SHOW next to “Trait” under “QTL”. Notice in the Query Overview the word “Trait” is now shown in a blue box to signify it will be included in the output.
5. We would like the output table to show the AnimalQTLdb QTL identifier. To do so, click SHOW next to the attribute “Qtl Id” under QTL in the Model Browser
6. The next step is to constrain the organism. The Model Browser shows that the “Organism” class is connected to QTL. Click the “+” next to “Organism” to expand its list of attributes. Click CONSTRAIN next to the “Name” attribute. You will again see a pop-up box with drop-down menu options. Select “=” and “Bos taurus” from their respective menus. Click “Add to query.” Notice that several more lines related to Organism have been added in the Query Overview, and these are indented to indicate that the Organism is an attribute of QTL. The blue box symbol next to the word “Organism” indicates that your query is joining data collections to each other (the QTL collection and

the Organism collection). Clicking this symbol allows you to indicate whether a relationship is required or optional, with the default being required.

7. The next few steps are to output identifiers of genes within the QTL regions.
8. Scroll down in the Model Browser, and expand the attributes of the “Overlapping Features” class. Click SHOW next to “DB identifier”. This will create a column in the output table listing identifiers of any genome features (e.g. genes, transcripts, exons) with chromosomal coordinates that overlap the QTL region coordinates.
9. Next you will limit the list of feature identifiers to the RefSeq gene set. Click CONSTRAIN next to the “Source” attribute under Overlapping Features. Within the pop-up box, select “=” and “RefSeq” from the pull-down menus. Add this filter to the query by clicking “Add to query.”
10. The next step is to further limit the list of identifiers to only genes using a Sequence Ontology term. The Sequence Ontology [11] is a standard controlled vocabulary used to describe components of genomes and genomic data. Click the “+” to expand “Sequence Ontology Term” under “Overlapping Features”, making sure that you stay within the correct subtree by following the vertical line that descends from “Overlapping Features”. If you are not careful, you could erroneously select the “Sequence Ontology Term” collection that descends directly from QTL. Click CONSTRAIN next to “Name” under the correct “Sequence Ontology Term” collection. From the pull-down menu of the pop-up box, select “gene” and “Add to query.”

At this point, query construction is complete. Looking at the Query Overview, notice that your query will output three columns: QTL id, QTL Trait and Sequence Feature DB identifier

(Fig.8D). Your query has four constraints: QTL Trait=Residual Feed Intake, Organism Name=Bos taurus, Overlapping Features Source=RefSeq, Sequence Ontology Term Name=Gene. Notice that the query joins three data collections: QTL, Organism and Overlapping Features. Also notice, the title of each data collection includes one or more words shown in brown font. If you click a word shown in brown, the Model Browser window will automatically adjust to show the corresponding data collection in the tree (Fig.9). This is convenient way to navigate to the correct region of the tree to select more attributes for a data collection.

Below the Model Browser the “Columns to Display” section shows the columns to be included in the output (Fig.8E). The output column order is not necessarily the same as shown in the Query Overview, but the order in which you added the column during query construction. You can drag the boxes to reorder the columns. With symbols in the blue boxes, you can eliminate columns, indicate that the output should be sorted based on a column, and add column descriptions.

You have several options once query construction is complete. You can click “Show results” to run the query (Fig.8E). You can select “Export XML” and copy the XML code to share the query with other users. If you export the XML, you can use the back button of your web browser to go back to the query to run it. If you are logged into MyMine, you can save the query by entering a name in the text box and clicking “Save query”. The saved query can be retrieved in the “Queries” section under MyMine. Finally, you can click the “Start building a template query” which will open a very similar page with your constructed query and additional options that allow you to name and describe the template. Clicking “Save template” or “Save and Run”

will promote the query to a finalized template which can be now found under the “Template” tab of the BovineMine navigation bar.

In the output of this example you will see the three columns, including one labeled “Overlapping Features DB identifier”. These identifiers are RefSeq Gene ids, because you constrained the overlapping features to be genes from the RefSeq gene set. Above the table you will see the number of rows of output. If you would like to save the genes for further analysis, you can click “Save as List” and then click “QTL→Overlapping Features”. In the pop-up box, you can rename the list and then click “Create List”. When you saved the list of overlapping features, you might have noticed that the number of features you saved is smaller than the number of rows in your table as some of the genes were found under more than one QTL. Keep in mind, that Animal QTLdb curates QTL from the literature, and assigns unique identifiers to independently published QTL, even if they occur in the same region.

Once the list is saved, you can use it with any template query that takes gene identifiers as input. Examples are “Gene → Gene Ontology” and “Gene → Pathway”. You can see the list via the Lists tab in the navigation bar. If necessary, click “View” in the black bar under the BovineMine navigation bar to toggle to the List View page. If you click on the name of the list, you will be presented with the List analysis page. For this example, you will notice the output columns are labeled as “sequence features” rather than genes, so gene enrichment analysis is not performed when you view the list. In order to run gene enrichment on the identifier list, use a template query, such as “Gene → Chromosomal Location”, that is sure to output all the genes, using this sequence feature list as the identifier constraint. Running a gene-based template query will

output the identifiers as genes rather than “sequence features”, as you can see in the output column headers. When you save the gene ids again, you will notice the default list name starts with “Gene” rather than “Sequence Feature”, and the resulting list can be used with the List Tool for a gene list analysis, including enrichment.

2.5.9 Regions Search

The “Regions” tab on the BovineMine navigation bar takes you to a web form that allows you to search for genomic features based on submitted chromosomal locations (chromosome ids and coordinates). The Regions search is particularly useful for bovine researchers who identify genomic variants through genome wide association studies and desire to know what genomic features exist within a specified range of the variant. Conversely, if you are interested in identifying all SNPs within a specified distance of a gene, the gene coordinates can be uploaded and the range adjusted to a desired distance. The results page provides all the features that overlap each region queried by the Regions search. The overlapped features can be exported in csv, tab delimited, gff3, or fasta file formats. Additionally, a new list can be created with the overlapped features by choosing a feature type for the “Create list by feature type” option. The second example in Subheading 2.5.11 utilizes the Regions search tool.

2.5.10 Column Management

The output tables of each query, list, or region search may be altered using the available tools. The top of each column header has a series of icons that may be used to sort the contents of the column, delete the column, hide the column from view, filter based on column contents, or summarize the results of the column. These functions can also be achieved using the “Manage

Columns” or “Manage Filters” buttons near the top of the page. The Manage Columns button allows you to remove entire columns, add columns, and prioritize sort order. After choosing the Manage Columns button, a pop-up window appears with a list of the columns currently available in the output table. Columns can be removed by clicking the red button to the right of a given column. Clicking the green “Add columns” button in the upper right portion of the pop-up window reveals a hierarchical data model browser similar to the one found in QueryBuilder. You can add new columns by selecting additional fields. The green button will now state “Add X new columns”, with X being the number of new fields chosen. The changes are finalized by clicking the blue “Apply Changes” button at the bottom. Columns can be filtered based on content by choosing the filter icon after the new column is added to the output table. All active filters can be edited or removed by clicking “Manage Filters”. The second example in Subheading 2.5.11 utilizes column management tools.

2.5.11 Two Step-by-Step Examples of Meta-Analysis using BovineMine

The Lists and Regions Search Tools are particularly useful for meta-analyses. An example is the meta-analysis of SNPs associated with fertility traits reported by Ortega *et al.* [12], in which SNPs common across different studies were identified. The comparison was relatively straightforward because the different studies used the same SNP assay. Sometimes the overlap of exact SNP identifiers or coordinates between studies does not occur due to differences in assays between studies. Another approach is to ask whether a SNP identified in one study is located within the vicinity of a SNP identified in another study. We will provide two examples of SNP

meta-analyses. In the first example, we will identify identical SNPs across studies. In the second example, we will identify SNPs from one study located within 20kb of SNPs from another study.

GWAS Meta-analysis Example 1:

Say you have identified a set of SNPs using the Bovine Illumina HD array, and would like to see how these SNPs align with the SNPs associated with the trait “Number of Services per Conception” (NSC) from Ortega *et al.* [12]. A challenge is that you would like to compare identifiers from the Bovine Illumina HD array with dbSNP rs identifiers from the publication.

1. The first step is to create a list using your study SNP ids.
 - a. Click the Lists tab in the BovineMine navigation bar.
 - b. Choose “SNP” from the “Select Type” pull-down menu and “B. taurus” from the “for Organism” menu.
 - c. The list of identifiers in Table 3, from the Bovine Illumina HD chip, is a simulated dataset created for this example. Paste these ids into the Lists Tool text box. After pasting identifiers from a PDF file, you should ensure that each row is on its own line and there are no extra whitespaces. Sometimes you may find that converting a PDF to a Word document may help to format information from tables.
 - d. Click “Create List”.
 - e. In the resulting webpage, save the list with the name “Study SNP List” in the text box and click the green “Save a list of 16 SNPs” button. You are taken to the

page showing the list you created. Notice the SNP chip identifiers have been replaced with dbSNP rs ids.

2. The next step is to create a list of SNPs associated with the trait “Number of Services Per Conception” from the Ortega et [12] publication.
 - a. If possible, access the web page for that publication (<http://www.sciencedirect.com/science/article/pii/S0022030217301819>). Scroll down to Table 3 in the article, and download the table as a comma separated value (csv) file. If you change the file extension to .txt, you will be able to open it in Excel. (See the next step if you cannot access the publication).
 - b. Paste the SNP identifiers from column 1 of the Ortega *et al.* [1] Table 3 into the text box. The SNP ids are provided in Table 4 of this chapter in case you cannot access that publication.
 - c. Click “Create List”.
 - d. After database lookup, the result indicates that one of the SNP ids is found in more than one BovineMine dataset. Select either of those as the allele does not matter, and click “Add” so it will be included in your final list. Provide a name for the list such as “SNPs for NSC” and click “Save a list of 16 SNPs”.
3. The last step of this example is to perform a List intersection. If you have navigated away from the previous page, click “Lists” in the BovineMine navigation bar to get back to the List tool. If you are presented with the Upload page rather than a page showing your lists, click “View” in the black bar below the BovineMine navigation bar. You will see both “Study SNP List” and “SNPs for NSC” (Fig.5). Any list that you have created is highlighted in purple, with “MY” in the left corner. Check the box next to each list. Click

“Intersect” in the “Action” bar above the list, and enter a new name, such as “Study_SNP_vs_SNPs_for_NSC” (Fig.5). The intersection shows that three of your study SNPs were also identified by the Ortega *et al.* [12] study. Click the name of the list to see the SNPs.

GWAS Meta-analysis Example 2:

Looking for exact matching SNPs between studies might have been too stringent since your population and assay were different from those used in the Ortega *et al.* [12] study. You would now like to see whether any of your SNPs are located within 20kb of the SNPs identified in the previous study.

1. Since you have already created SNP lists, the next step is to create a list of regions for the “SNPs for NSC” identifiers to use in the Regions Search tool.
 - a. If you are not already viewing your lists, click “Lists” in the BovineMine navigation bar, and if necessary, click “View” in the black bar below the navigation bar.
 - b. Click the name of the list “SNPs for NSC”.
 - c. Click “Manage Columns” above the table (Fig.10A).
 - d. In the pop-up menu, remove the unneeded Reference Allele and Alternate Allele columns by clicking the red circles (Fig.10B).
 - e. Click the green “+Add a Column” box (Fig.10B).
 - f. Click the “+” sign next to “Chromosome Location”. Then click “Start” and “End”. Although the SNP is a single coordinate, the Region Search tool requires a Start and End coordinate (Fig.10C).

- g. To retrieve the chromosome id, click the “+” sign next to “Located On”, and then click “DB identifier” (Fig.10C).
 - h. Click the green “Add 3 Columns” box (Fig.10C).
 - i. Notice columns have been added to the column list. However, the order needs to be modified to correctly format the location information for the Regions Search. Use the up arrow to move “Located On >> DB identifier” above “Chromosome Location >> Start”. Then click the blue “Apply Changes” box (Fig.10D).
 - j. The next step is to export the coordinates so they can be uploaded to the regions search. Click the “Export” button above the table (Fig.10E).
 - k. Enter a file name. Then mouse over “All Columns” to change that default setting so that only selected columns are exported. Click the toggle next to “SNP > SNP rsID” so that it will not be included in the output, since the Regions Search tool does not accept identifiers (Fig.10F).
 - l. Click “Download File” and save the file on your computer.
 2. The next steps are to perform a Regions Search for all known SNPs within 20kb of your coordinates. Click the “Regions” tab in the BovineMine navigation bar.
 - a. In the Regions Search menu (Fig.11) select “B. taurus” from the “1. Select Organism” pull-down menu.
 - b. Click the square next to “2. Select Feature Types” to uncheck all options and then click the box next to “SNP” as the chosen feature option.
 - c. Upload the file you just saved.
 - d. Type “20kb” into the text box of “4. Extend your regions at both sides.”
 - e. Click “Search” to run the Regions Search tool.

3. After the Region Search is successfully run you are presented with an output page listing each of the regions and the numbers of SNPs identified within the regions (Fig.11). At this point you could download any results for any region separately, with a choice of formats, or you could create a SNP list for each region separately. For this example, we want to save a list of all the SNPs, so use the “Create List by feature type” button above the output after selecting “SNP” in the pull-down menu and click “Go”. This action creates a new list that is visible on the List View page. You are not given the opportunity to provide a name for the list; it is assigned a default name that starts with “all_regions_SNP_list”. If you are logged into MyMine, you can change the name by clicking the MyMine tab, selecting Lists in the red tool bar, and clicking the pencil symbol next to the list name to edit it.
4. The next step is to perform a List intersection to identify SNPs from your study that are also found in the list of all SNPs that are within 20kb of SNPs identified by Ortega *et al.* [12]. Go to the List View page by clicking “View” in the black bar below the BovineMine navigation bar. Check the box next to each list. Click “Intersect” in the “Action” bar above the list, and enter a new name, such as “Study_SNP_vs_SNPs_within 20kb_SNPS_for_NSC_intersection”. The intersection shows that nine of your study SNPs are located within 20kb of the SNPs identified by the Ortega *et al.* [12] study.

The two examples above provide us with very limited information. You can use the lists in a variety of ways to acquire more information. For example, you can use column management functions to determine whether these SNPs are located within genes.

1. If you are not already on a List Analysis page showing your list, click on the List name on the List View page.
2. Click “Manage Columns” above the List Analysis table.
3. Click the green “+Add a Column” button.
4. Add the following columns:
 - a. Scroll down, open “Overlapping Features” and select both “DB identifier” and “Source”
 - b. Scroll down further, open “Sequence Ontology Term” and select “Name”, being sure that you selected the “Sequence Ontology Term” within “Overlapping Features”.
5. Click the green “Add 3 new columns” button.
6. Click “Apply changes”.
7. You can see the new columns added to the output table (Fig.12). You can see in the Sequence Ontology Term column that there are several feature types. To get only genes, click the histogram icon in the column header, check “gene”, and select “Restrict table to matching rows” in the blue “Filter” pull down menu (Fig.12).
8. Now only rows with genes are shown. The “Overlapping Features Source” column indicates the genes are from three gene sets.
9. To limit the output to RefSeq genes filter the column using the histogram icon in the Overlapping Features Source column, similar to step 7.
10. Save this list of overlapping features using the “Save as List” pull-down menu, naming the list “RefSeq Genes Overlapping SNPs”. You will notice that you will save “7

Sequence Features” even though you have 8 rows in the table, due to one gene (515321) overlapping two SNPs.

11. Since the list consists of gene ids, you can use it in any template query that accepts gene ids as input. Go to the BovineMine Home page and locate the “Gene → Pathways” template query under the Function template category. Click the template name, and check the box next to “constrain to be”, make sure “IN” is selected, and choose the list “RefSeq Genes Overlapping SNPs” in the pull-down menu (Fig.13). The output shows that your genes are annotated with both Reactome and KEGG pathways.

The previous examples showed you how to compare SNP lists from different studies using a combination of the List Tool and Regions Search, identify genes overlapping SNPs, and retrieve pathway information for the genes. BovineMine provides many alternatives at each of the steps. For example, rather than filtering the features overlapping SNPs for genes, you could have filtered for QTL, saved a list of QTL ids, and then used a template query to determine the traits. Another use of BovineMine related to GWAS is to identify genes in the vicinity of SNPs, along with GO terms or pathway information, in order to perform SNP-based Gene Set Enrichment Analysis (GSEA-SNP) (e.g. [13]). One could create a gene annotation data set for genes within a specified distance to all SNPs on a SNP chip by first using the List Tool to create a SNP list, followed by saving a list of SNP coordinates to be loaded into Regions search box, and then performing the Regions search with “Gene” selected as the feature type. In the absence of SNP ids, as may be the case in a genome resequencing project, the Regions search rather than the List Tool could be the starting point. After the gene list is saved, it can be used with the template queries to gather information about the genes.

3. Notes

3.1 BovineMine Release for this Chapter

The most current release of BovineMine can be accessed from the main BGD navigation bar, or with the following URL: <http://bovinegenome.org/bovinemine/>. This chapter is based on BovineMine release 1.3, which will always be available here:

<http://bovinegenome.org/bovinemine-release-1.3/>. You can perform the examples anonymously, but it is advisable to login to your MyMine account so that you can save your work.

3.2 Computing Expression Values and Variant Effects

We trim Illumina RNA-seq reads for adaptors using Fastq-MCF (<https://code.google.com/p/ea-utils/wiki/FastqMcf>); trim for quality using DynamicTrim [14] and align reads to the bovine UMD3.1 genome assembly using TopHat2 [15]. We determine FPKM (Fragments Per Kilobase of transcript per Million mapped reads) and normalized read counts for each expression dataset for transcripts in the Ensembl and RefSeq gene sets using cuffquant and cuffnorm, which are part the Cufflinks package [16]. We use the Ensembl Variant Effect Predictor [17] to predict variant effects for the bovine gene sets.

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Figure Legends

Figure 1. A) To assist users in selecting JBrowse tracks to visualize expression of a specific gene, BGD includes a quick lookup tool to retrieve pre-computed expression levels based on RNA-seq. The tool is available via the Lookup Tool pull down menu of the BGD navigation bar. The lookup tool pulls data from BovineMine, where additional RNA-seq metadata can be retrieved. B and C) Once a tissue or sample of interest is identified, the JBrowse faceted track selector facilitates choosing RNA-seq tracks for viewing. RNA-seq tracks are categorized according to both Organ System and Brenda Tissue Ontology, and are searchable based on metadata such as sample name, SRA identifier and tissue. D) Each RNA-seq dataset is available in six different visualizations depending on the user's objective. This figure shows RNA-seq Junctions and Collapsed BAM tracks.

Figure 2. The BovineMine homepage allows you to initiate analysis by using a query form for "Quick Search" or "Quick List" or by using predefined template queries organized into major data categories. Alternatively, you could select a tab in the BovineMine navigation bar for the more advanced search options available with the QueryBuilder, List Tool and Regions search.

Figure 3. The quick search box employs a full text search and identifies all records containing the search term. A search summary page allows you to filter by feature class and/or species. Filtered summaries can be further saved as a list by using the “Create List” button. Clicking the orange name of a record leads to a report page (not shown).

Figure 4. A) The List Tool Upload page takes lists of identifiers as input. The correct data type must be selected. B) After a database lookup is performed, a page listing matching identifiers is provided with options to name and save the list. C) List analysis results in a table, which, like all tables in BovineMine, may be altered using icons within the column headers and using the Manage Columns, Manage Filters and Manage Relationships buttons. This figure shows the creation of the DE Gene List in example 2.5.6.

Figure 5. The List View page shows user-made lists highlighted in purple. Once a list intersection is performed, a new list appears. This figure shows the intersection performed in the first example in Subheading 2.5.11.

Figure 6. Using the List Tool with a list of gene identifiers generates enrichment widgets that include options to select test correction, p-value and background population. It is recommended that BovineMine users always select an alternative background population, since the default background population is all genes annotated with the appropriate datatype; these genes may be from more than one gene set (e.g both Ensembl and RefSeq). Alternative gene lists, including premade gene set lists and all user-saved lists, are available by clicking “Change” under to “Background Population”. This figure, showing the analysis from example 2.5.6, demonstrates

the difference in enrichment results after changing the background population from the default to the list of all expressed genes identified in the study [9].

Figure 7. Predefined template queries are provided for commonly used queries. The results are provided in tables, which can be altered using the icons in the column headers or the column management buttons above the table. Furthermore, you can save lists of different identifiers within the table by clicking “Save as List” and choosing the column of identifiers you wish to save. This figure shows the example provided in Subheading 2.5.7.

Figure 8. These figures show the steps in the QueryBuilder example in Subheading 2.5.8. The QueryBuilder allows you to develop custom queries incorporating multiple data sources. A) From the QueryBuilder page, you can browse the data model, import queries in XML format, or view saved queries. The QueryBuilder entry page also reports your most recent query history. Query creation begins by selecting a data class and clicking select. B) The model browser allows you to create query constraints. C) When you click CONSTRAIN a pop-up menu allows you to enter information. Here the QTL output is constrained to the Trait “Residual Feed Intake”. D) The final Query Overview from the 2.5.8 example shows that the query will output three columns (QTL id, QTL Trait and Sequence Feature DB identifier) and the query has four constraints: (QTL Trait=Residual Feed Intake, Organism Name=Bos taurus, Overlapping Features Source=RefSeq, Sequence Ontology Term Name=Gene). E) The output columns and their order in the final results table are illustrated by blue boxes that may be rearranged by dragging and dropping. In addition to running, a custom query can be named and saved, exported for sharing and developed into template query.

Figure 9. After adding each query component, the view in the Model Browser resets to the top of the tree. The Query Overview provides a trick that allows you to easily jump back to a region of the Model Browser tree to select more outputs or constraints. A) After the Sequence Feature DB Identifier was added to the query, the Model Browser view was reset. In the Query Overview, notice the words “Sequence Feature” in brown font. B) Clicking the word “Sequence Feature” in the Query Overview allows you to navigate back to the associated data collection in the Model Browser to select additional Sequence Feature attributes or constraints.

Figure 10. This figure shows column management steps used in the second example described in Subheading 2.5.11. A) Above every table are the column management buttons “Manage Columns”, “Manage Filters” and “Manage Relationships”. Tables can also be modified using the icons in the column headers. B) The Manage Columns menu allows you to remove existing columns and add new columns. C) If you choose to add new columns, a hierarchical data model tree is provided, allowing you to select attributes as new output columns. The attributes you select are highlighted in blue. D) After selecting attributes and clicking “Apply Changes”, you return to the main Manage Columns menu, where you can reorder the columns using up and down arrows. E) Clicking “Apply Changes” in the Manage Columns menu generates the new table. F) Clicking “Export” opens the Download menu. In this example, we wished to export only the SNP coordinates, not the SNP ids, so we use the toggle next to “SNP > SNP id” to remove it from the list of columns to be output in the tsv file.

Figure 11. The Regions search upload menu takes input of genomic coordinates in the text box, or uploaded as a file. Examples of accepted coordinate formats are provided above the text box. To extend the search region, either enter the distance in the text box or use the slider. The output of a Regions search is a page that lists each region with the numbers of features found. You can download data for each region in various formats, or you can generate a list of features found in all regions using “Create List by Feature Type.” This figure shows the Regions search performed in the second example described in Subheading 2.5.11.

Figure 12. This figure shows the table generated in step 7 of the second example described in Subheading 2.5.11. The histogram icon in each column header produces a column summary. Clicking this icon in the Sequence Ontology Term Name column shows all the feature types overlapping the SNPs. Checking the box next to “gene”, then selecting “Restrict table to matching rows” in the Filter pull-down menu modifies the table so that only gene features are listed. Following this step, a list of gene ids can be generated.

Figure 13. Template queries that take a single identifier as input can also be used with lists of identifiers of the appropriate data type. When lists are available, the option to “constrain to be” is automatically provided. A pull-down menu with a default “IN” can be changed to “NOT IN”. All available lists of the appropriate data type, including user-made lists, are provided for selection in the list pull-down menu. This figure shows the result of using the “Genes Overlapping SNPs” list from the second example described in Subheading 2.5.11 in the Gene → Pathway template query.

Tables

Table 1. BovineMine Data Sources

Data Source	Reference
AnimalQTLdb	[10]
BioCyc	[18]
BioGRID	[19]
Bovine Genome Assembly UMD3.1.1	[20]
Bovine HapMap	[21]
Bovine Official Gene Set	[22]
dbSNP	[23]
dbVar	[24]
EnsemblCompara	[25]
Ensembl Genes	[26]
Goat Genome Assembly ARS1	[27]
Gene Ontology	[28]
HomoloGene	[29]
IntAct	[30]
InterPro	[31]
KEGG	[32]
OrthoDB	[33]
PubMed	[34]
Reactome	[35]
RefSeq	[36]
Sequence Read Archive	[37]
Sheep Genome Assembly OAR_v3.1	[38]
SNPchiMp	[39]
Treefam	[40]
UniProt	[41]
UniProt-GOA	[42]

Table 2. Primary gene or protein identifiers used in data sets for different species at BovineMine. Information in this table is useful when building a query that involves a dataset that uses a specific source of gene identifier. The first three rows of the table indicate which primary gene and protein data sets are available for each species. The second part of the table indicates which of the first three data sets are related to other data sets in BovineMine, and which type of identifier is used for those relationships. The Data Class column in the second part of the table indicates the data class that has a direct relationship to the data set listed in the second column. E=Ensembl, R=RefSeq, U=UniProt.

Data Class ↓	Species →	<i>Bos taurus</i>	<i>Capra hircus</i>	<i>Ovis aries</i>	<i>Sus scrofa</i>	<i>Equus caballus</i>	<i>Canis familiaris</i>	<i>Mus musculus</i>	<i>Rattus norvegicus</i>	<i>Homo sapiens</i>
	Data Set ↓									
Gene	Ensembl	E		E						
Gene	RefSeq	R	R	R						
Protein	UniProt	U	U	U				U	U	U
Gene	BioCyc	E						E		E
Gene	BioGRID	R						R	R	R
Gene	Ensembl Compara	E			E	E	E	E	E	E
Gene	Gene Symbols	E, R	R	E, R				E, R	E, R	E, R
Gene	GO Annotations	E, R	R	E, R				R	R	R
Gene	Homologene	R					R	R	R	R
Gene	IntAct	E		E				E	E	E
Gene	KEGG	R			R	R	R	R	R	R
Gene	OrthoDB	E	R	E	E	E	E	E	E	E
Gene	Publications	E, R	R	R				R	R	R
Gene	TreeFam	E						E	E	E
Gene	Reactome	E, R								
Gene	UniProt	E, R	R	E, R				R	R	R
Transcript	Expression	E, R								
Transcript	dbSNP variant consequences	E, R								
Protein	InterPro	U	U	U				U	U	U
Protein	Reactome	U						U	U	U

Table 3. Identifiers for step 1c of the GWAS Meta-analysis in the first example described in Subheading 2.5.11.

ARS-BFGL-NGS-34049
ARS-BFGL-NGS-67989
ARS-USMARC-670
BFGL-NGS-116469
BovineHD0100038154
BovineHD0300002060
BovineHD0500025143
BovineHD0600006358
BovineHD0700015348
BovineHD0700015365
BovineHD0700028738
BovineHD1300008936
BovineHD1400004569
BovineHD1800015205
BovineHD2500000403
Hapmap41181-BTA-120938

Table 4. Identifiers for step 2b in the GWAS Meta-analysis in the first example described in Subheading 2.5.11.

rs133674837
rs110217852
rs137601357
rs109621328
rs133747802
rs109443582
rs109137982
rs41893756
rs109262355
rs109830880
rs110828053
rs111015912
rs134264563
rs109813896
rs109629628
rs110660625

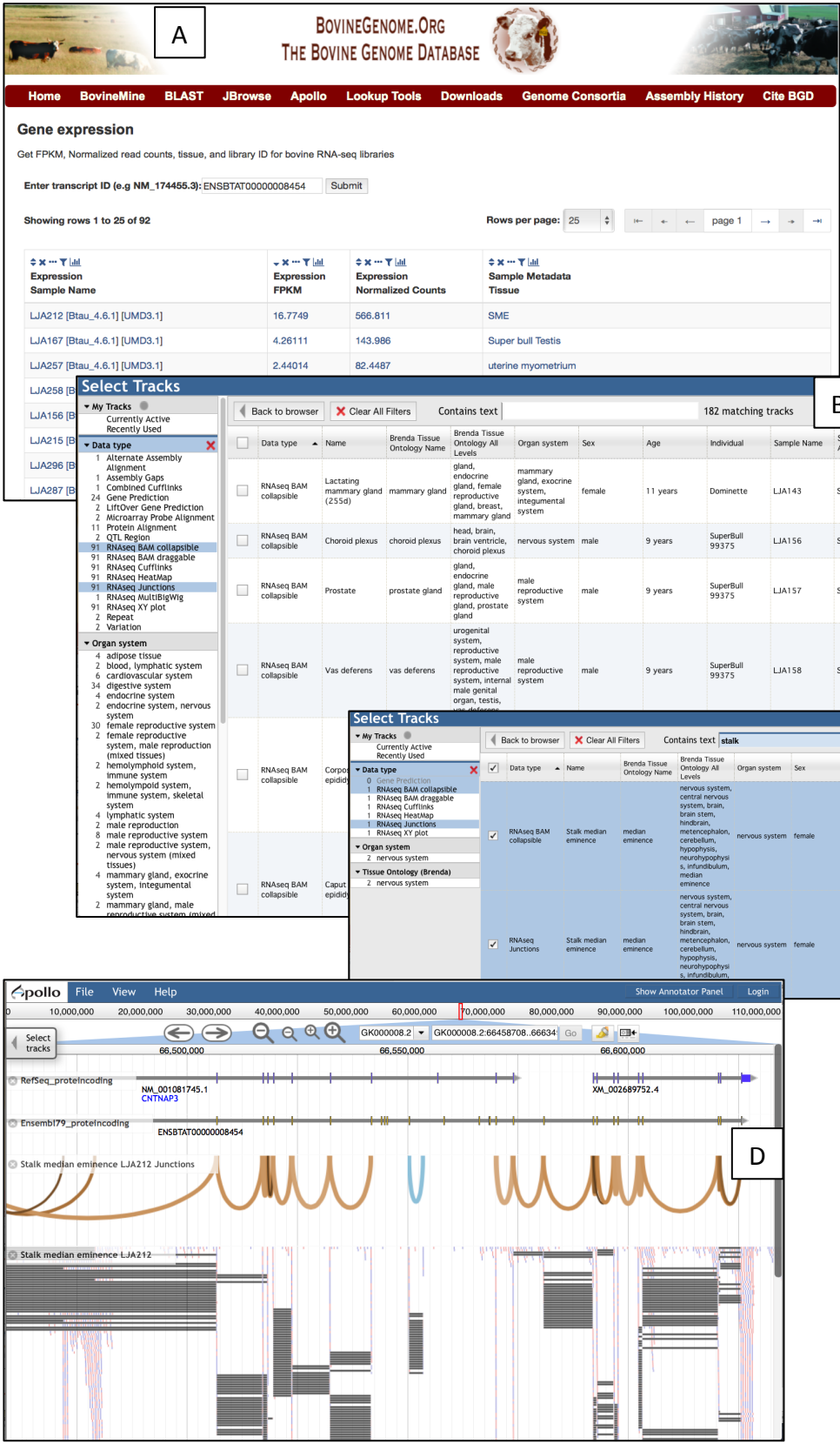


Figure 1

BovineMine v1.3 An integrated data warehouse for the [Bovine Genome Database](#) help | cite

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Search:

Quick Search

Search BovineMine. Enter names, identifiers or keywords for genes, proteins, ontology terms, authors, etc. (e.g. RPL24, RCAN1, NM_001040473.2, 282087, ENSBTAG00000013066, IGF2_BOVIN, rs385910977)

e.g. IGF2, ENSBTAG00000013066, IGF2

SEARCH

Quick List

Enter a list of identifiers.

Gene

515523, BT18560, BTG1, ENSBTAG00000013066

[advanced](#)

ANALYZE

Welcome Back!

BovineMine integrates the bovine reference genome assembly (UMD3.1.1) with many other biological data sets, including genomes of other species. The sheep (Oar_v3.1) and goat (ARS1) genomes allow comparison across ruminants. Model organism data (human, mouse, rat) allow well-curated data sets to be applied to ruminants using orthology.

TUTORIAL

[GENES](#)
[EXPRESSION](#)
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[FUNCTION](#)
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[VARIATION](#)
[ALIAS AND DBXREF](#)
[ENTIRE GENE SET](#)

BovineMine includes *B. taurus* transcript expression values, which we compute based on aligned RNAseq reads. SRA Metadata and BRENDA tissue ontology terms are also included.

Query for expression:

- Bovine Gene → Transcripts → Expression
- Bovine QTL → Transcripts
- Transcript ID → Expression, Metadata and BRENDA Tissue Ontology
- Gene → Bovine Homologues → Bovine Transcripts → Bovine Expression

Figure 2

Quick Search

Search BovineMine. Enter names, identifiers or keywords for genes, proteins, ontology terms, authors, etc. (e.g. RPL24, RCAN1, NM_001040473.2, 282087, ENSBTAG00000013066, IGF2_BOVIN, rs385910977)

IGF2

SEARCH

Search results 1 to 100 out of 740 for IGF2

<< First < Previous | Next > Last >>

Categories

Hits by Category

- Publication: 686
- Protein: 24
- mRNA: 16
- Gene: 9
- Protein Domain: 3
- Interaction Experiment: 1
- UniProt Feature: 1

Hits by Organism

- H. sapiens: 18
- B. taurus: 13
- M. musculus: 8
- O. aries: 5
- C. hircus: 3
- R. norvegicus: 2

Type	Details	Score
Gene	281240 - IGF2 Source: RefSeq Length: 27360 [FASTA...] Chromosome: CK000029.2: 50037872-50065231 Location: B. taurus Organism:
Gene	ENSBTAG00000013066 ENSBTAG00000013066 IGF2 Source: Ensembl 84 Length: 18605 [FASTA...] Chromosome: CK000029.2: 50046626-50065230 Location: B. taurus Organism:
Gene	100861277 - IGF2 Source: RefSeq Length: 7901 [FASTA...] Chromosome: NC_030836.1: 50430375-50438275 Location: C. hircus Organism:
	443325 - IGF2	

Search results 1 to 16 out of 16 for IGF2

Category restricted to MRNA

0.018s

Categories

Category: MRNA

show all

Hits by Organism

- B. taurus: 11
- O. aries: 3
- C. hircus: 2

CREATE LIST

Type	Details	Score
<input type="checkbox"/> mRNA	XM_005227273.1 Source: RefSeq Length: 4006 [FASTA...] Chromosome: GK000029.2: 50037926-50065231 Location:
<input type="checkbox"/> mRNA	NM_174087.3 Source: RefSeq Length: 3796 [FASTA...] Chromosome: CK000029.2: 50046626-50065231 Location:
<input type="checkbox"/> mRNA	ENSBTAT00000017372 Source: Ensembl 84 Length: 3795 [FASTA...] Chromosome: CK000029.2: 50046626-50065230 Location:
<input type="checkbox"/> mRNA	XM_005227272.1 Source: RefSeq Length: 4304 [FASTA...] Location:

Figure 3

Create a new list

Select the type of list to create and either enter in a list of identifiers or upload identifiers from a file. A search will be performed for all the identifiers in your list.

- Separate identifiers by a **comma, space, tab or new line**.
- Qualify any identifiers that contain whitespace with double quotes like so: "even skipped".

Select Type:

for Organism:

Type/Paste in identifiers (click to see an example with different types of IDs) (example to query a list of milk production genes)

```

ENSBTAG00000009687
ENSBTAG000000018972
ENSBTAG00000001144
ENSBTAG000000012112
ENSBTAG000000016508
ENSBTAG00000005357
ENSBTAG000000034867
ENSBTAG000000018449
ENSBTAG00000000562
ENSBTAG000000044175

```

or Upload identifiers from a .txt file... no file selected

Match on case

Choose a name for the list

Background Gene List (e.g. Smith 2013)

Add additional matches

You entered: 10963 identifiers
We found: 10923 Genes

Why are the numbers different? See below.

Summary

Direct Hits

Page 1 of 2185 | 1 2 3 4 5 ... 2185 | 5 rows per page

Identifier you provided	Match						
symbol	organism short name	name	length	secondary identifier	source	primary identifier	class
ENSBTAG00000016878	WDR59 B. taurus	80176	ENSBTAG00000016878	Ensembl 84	ENSBTAG00000016878	Gene	
ENSBTAG00000015546	MINA B. taurus	33127	ENSBTAG00000015546	Ensembl 84	ENSBTAG00000015546	Gene	
ENSBTAG00000014215	B. taurus						

List Analysis for Background Gene List (10923 Genes)

Showing 1 to 25 of 10,923 rows Rows per page: 25

Gene ID	Gene Secondary Identifier	Gene Symbol	Gene Name	Gene Source	Gene Length	Gene Organism
100124521	NO VALUE	SLC25A37	NO VALUE	RefSeq	6472	B. taurus
100125265	NO VALUE	GALNT4	NO VALUE	RefSeq	5302	B. taurus
100125285	NO VALUE	SNX21	NO VALUE	RefSeq	1700	B. taurus

Figure 4

Upload | View Search: *e.g. ATP synthase, AT5G2_B1* GO

Lists
View your own and public lists, search by keyword and compare or combine the contents of lists. Click on a list to view graphs and summaries in an analysis page, select lists using checkboxes to perform set operations. Click 'Upload' above to import a new list.

Filter: Filter: MY -- filter by a tag -- Reset

Actions: Union | Intersect | Subtract | Asymmetric Difference | Copy Delete Options: Show descriptions

- SNPs for NSC 16 SNPs
- Study SNP List 16 SNPs
- DE Gene List 4595 Genes
- Background Gene List 10923 Genes

Intersect

Enter a new List name:
Study_SNP_vs_Save



Upload | View Search: *e.g. ATP synthase, AT5G2_B1* GO

Created list "Study_SNP_vs_SNP_for_NSC" as INTERSECT of SNPs for NSC and Study SNP List. Hide

Lists
View your own and public lists, search by keyword and compare or combine the contents of lists. Click on a list to view graphs and summaries in an analysis page, select lists using checkboxes to perform set operations. Click 'Upload' above to import a new list.

Filter: Filter: MY -- filter by a tag -- Reset

Actions: Union | Intersect | Subtract | Asymmetric Difference | Copy Delete Options: Show descriptions

- Study_SNP_vs_SNP_for_NSC 3 SNPs
- SNPs for NSC 16 SNPs
- Study SNP List 16 SNPs
- DE Gene List 4595 Genes
- Background Gene List 10923 Genes

Figure 5

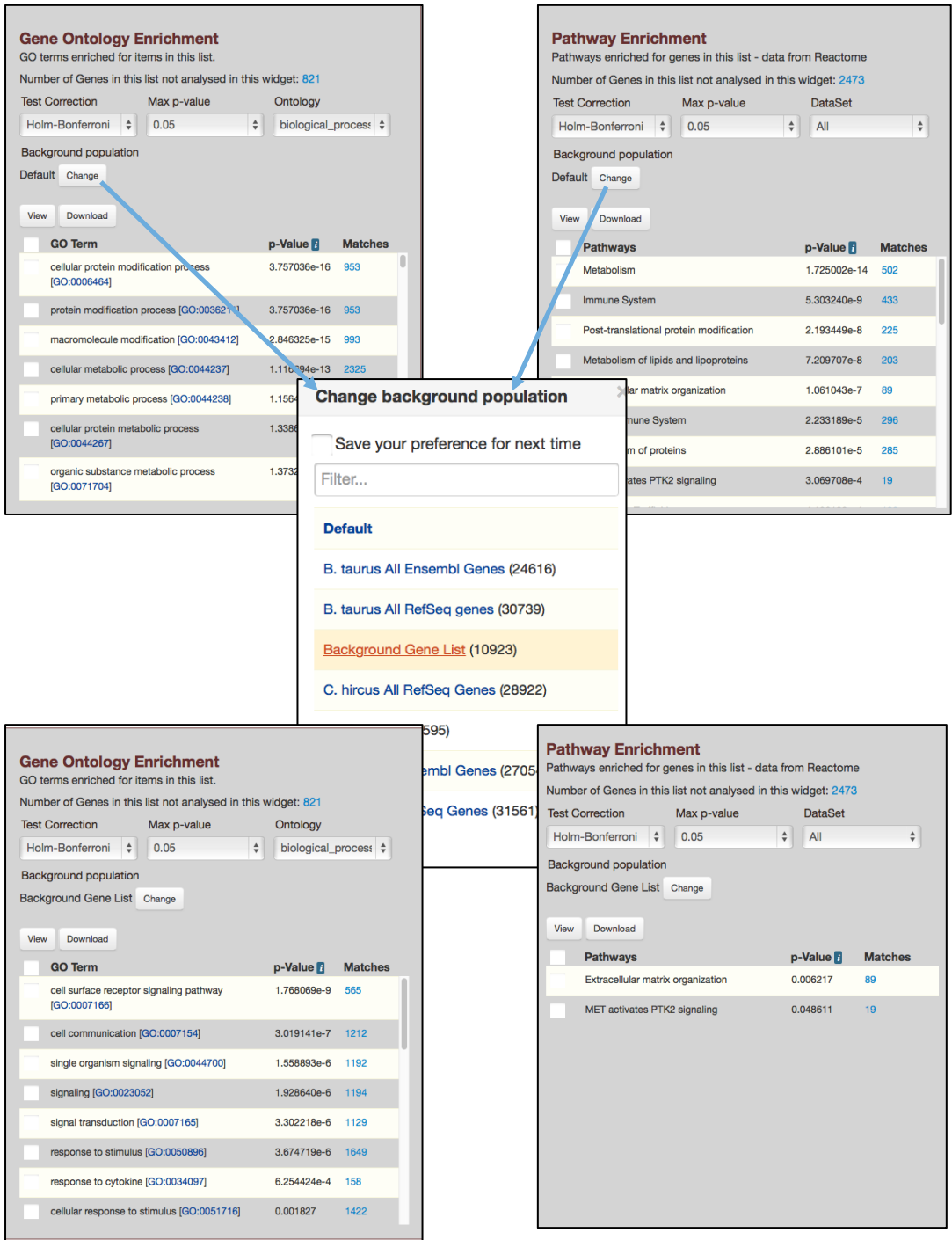


Figure 6

Bovine Gene → **Transcripts** → **Expression**
 Given a bovine gene id or symbol, retrieve transcripts and expression levels, optionally filtered by tissue and/or expression level.

Gene > Gene
 LOOKUP: 404130
 constrain to be IN saved Gene list B. taurus All Ensembl Genes

Expression Metadata > Tissue
 optional ON / OFF
 255d lactating mammary gland

Expression > FPKM
 > 10

Expression > Normalized Counts
 > 0

[web service URL](#) | [Perl](#) | [Python](#) | [Ruby](#) | [Java](#) | [help](#) | [export XML](#)

Trail: Query
Bovine Gene → **Transcripts** → **Expression**
 Given a bovine gene id or symbol, retrieve transcripts and expression levels, optionally filtered by tissue and/or expression level.

Showing rows 1 to 4 of 4

Gene ID	Isoform Transcript Identifier	Sample Metadata SRA Sample Accession	Expression Sample Name	Sample Metadata Tissue	Sample Metadata Brenda Tissue Ontology name	Expression FPKM	Expression Normalized Counts
404130	NM_205794.1	SRS734278	LJA167	Super bull Testis	testis	29.5083	777.245
404130	NM_205794.1	SRS734274	LJA156	Choroid plexus	choroid plexus	12.3818	326.239
404130	NM_205794.1	SRS734226	LJA270	Semimembranosus (top/inside round)	semimembranosus	11.3026	297.717
404130	NM_205794.1	SRS734198	LJA266	Biceps femoris (bottom/outside round)	biceps femoris	10.5568	278.065



Trail: Query
Bovine Gene → **Transcripts** → **Expression**
 Given a bovine gene id or symbol, retrieve transcripts and expression levels, optionally filtered by tissue and/or expression level.

Showing rows 1 to 4 of 4

Gene ID	Isoform Transcript Identifier	Sample Metadata SRA Sample Accession	Expression Sample Name	Sample Metadata Tissue	Sample Metadata Brenda Tissue Ontology name	Expression FPKM	Expression Normalized Counts
404130	NM_205794.1	SRS734278	LJA167	Super bull Testis	testis	29.5083	777.245
404130	NM_205794.1	SRS734274	LJA156	Choroid plexus	choroid plexus	12.3818	326.239
404130	NM_205794.1	SRS734226	LJA270	Semimembranosus (top/inside round)	semimembranosus	11.3026	297.717
404130	NM_205794.1	SRS734198	LJA266	Biceps femoris (bottom/outside round)	biceps femoris	10.5568	278.065

Context menu options:
 Expression > Isoform > Gene (1 Gene)
 Expression > Isoform (1 Transcript)
 Expression > Sample Metadata (4 Expression Metadata)
 Expression (4 Expressions)
 Expression > Isoform > Gene > Organism (1 Organism)
 Pick items from the table

Figure 7

QueryBuilder

Advanced users can use a flexible query interface to construct their own data mining queries. The QueryBuilder lets you view the data model, apply constraints and select output. You can also export queries to share them with others.

[Browse data model](#)
[Import query from XML](#)
[View saved queries](#)

Select a Data Type to Begin a Query

Click on a class name for a description or double click on a class name to create a new query starting at that class

- Probe
- Protein
- Protein Domain
- Protein Domain Region
- Publication
- QTL**
- rRNA
- Repeat Region
- SNP
- SO Term

Query History

Queries that you have run during this session

QUERY NAME	CREATED	APPROX ROWS	START	RESULTS FORM
query_1	2017-05-02 16:21	n/a	QTL	Qtl Id DB Ident
query_2	2017-05-02 16:26	n/a	Expression	Gene ID Tissue Breeds Counts

Model browser

Browse through the classes and attributes. Click on [SUMMARY](#) links to add summary of fields to the results table or on [SHOW](#) links to add individual fields to the results. Use [CONSTRAIN](#) links to constrain a value in the query.

- QTL [SUMMARY](#) [CONSTRAIN](#)
- Abbreviation [SHOW](#) [CONSTRAIN](#)
- Additive Effect [SHOW](#) [CONSTRAIN](#)
- Bayes Value [SHOW](#) [CONSTRAIN](#)
- Gene Identifier [SHOW](#) [CONSTRAIN](#)
- Length Integer [SHOW](#) [CONSTRAIN](#)
- DB identifier [SHOW](#) [CONSTRAIN](#)
- Qtl Id [SHOW](#) [CONSTRAIN](#)
- Symbol [SHOW](#) [CONSTRAIN](#)
- Trait [SHOW](#) [CONSTRAIN](#)
- Type [SHOW](#) [CONSTRAIN](#)
- Chromosome Chromosome [SUMMARY](#) [CONSTRAIN](#)
- Chromosome Location Location [SUMMARY](#) [CONSTRAIN](#)
- Data Sets Data Set [SUMMARY](#) [CONSTRAIN](#)
- Locations Location [SUMMARY](#) [CONSTRAIN](#)
- Organism Organism [SUMMARY](#) [CONSTRAIN](#)
- Overlapping Features Sequence Feature [SUMMARY](#) [CONSTRAIN](#)
- Sequence Sequence [SUMMARY](#) [CONSTRAIN](#)
- Sequence Ontology Term SO Term [SUMMARY](#) [CONSTRAIN](#)
- Synonyms Synonym [SUMMARY](#) [CONSTRAIN](#)

Query Overview

no fields constrained

Constraint logic:
no constraints

Constraint for QTL > Trait

Constrain

Choose a filter

Filter query results on this field having a specific value

QTL > Trait
 = Residual Feed Intake [Add to query](#)

Filter query results on this field having any value or not

Has no value Has a value [Add to query](#)

Query Overview

QTL

- Qtl Id [X](#)
- Trait [X](#)
- = Residual Feed Intake [X](#) [A](#)
- Organism Organism [X](#) [B](#)
- Name [X](#)
- = Bos taurus [X](#) [B](#)
- Overlapping Features Sequence Feature collection [X](#) [C](#)
- DB identifier [X](#)
- Source [X](#)
- = RefSeq [X](#) [C](#)
- Sequence Ontology Term SO Term [X](#) [D](#)
- Name [X](#)
- = gene [X](#) [D](#)

Constraint logic: A and B and C and D

A and B and C and D

Fields selected for output

Columns to Display

Use the [SHOW](#) or [SUMMARY](#) links to add fields to the results table. Click and drag the blue output boxes to choose the output column order. Click [\[1\]](#) to choose a column to sort results by, click again to select ascending [\[1\]](#) or descending [\[1\]](#). Use the [REMOVE ALL](#) link to remove all fields from the results table.

[REMOVE ALL](#)

- QTL > Trait (no description) [\[1\]](#)
- QTL > Qtl Id (no description) [\[1\]](#)
- QTL > Overlapping Features > DB identifier (no description) [\[1\]](#)

[Show results](#)

[web service URL](#) | [Perl](#) | [Python](#) | [Ruby](#) | [Java \[help\]](#) | [Export XML](#)

[Start building a template query](#)

qtl_residual_feed_intake [Save query](#)

Figure 8

Model browser

Browse through the classes and attributes. Click on **SUMMARY** links to add summary of fields to the results table or on **SHOW** links to add individual fields to the results. Use **CONSTRAIN** links to constrain a value in the query.

QTL

- Abbreviation **SHOW** **CONSTRAIN**
- Additive Effect **SHOW** **CONSTRAIN**
- Bayes Value **SHOW** **CONSTRAIN**
- Gene Identifier **SHOW** **CONSTRAIN**
- Length Integer **SHOW** **CONSTRAIN**
- DB identifier **SHOW** **CONSTRAIN**
- Qtl Id **SHOW** **CONSTRAIN**
- Symbol **SHOW** **CONSTRAIN**
- Trait **SHOW** **CONSTRAIN**
- Type **SHOW** **CONSTRAIN**
- Chromosome Chromosome **SUMMARY** **CONSTRAIN**
- Chromosome Location Location **SUMMARY** **CONSTRAIN**
- Data Sets Data Set **SUMMARY** **CONSTRAIN**
- Locations Location **SUMMARY** **CONSTRAIN**
- Organism Organism **SUMMARY** **CONSTRAIN**
- Overlapping Features Sequence Feature **SUMMARY** **CONSTRAIN**

Query Overview

QTL

Qtl Id **X**

Trait **X**

= Residual Feed Intake **X** (A)

Organism Organism **X**

Name **X**

= Bos taurus **X** (B)

Overlapping Features Sequence Feature collection **X**

DB identifier **X**

Show SequenceFeature in the model browser

Constraint logic: A and B

A and B



Model browser

- Length Integer **SHOW** **CONSTRAIN**
- DB identifier **SHOW** **CONSTRAIN**
- Qtl Id **SHOW** **CONSTRAIN**
- Symbol **SHOW** **CONSTRAIN**
- Trait **SHOW** **CONSTRAIN**
- Type **SHOW** **CONSTRAIN**
- Chromosome Chromosome **SUMMARY** **CONSTRAIN**
- Chromosome Location Location **SUMMARY** **CONSTRAIN**
- Data Sets Data Set **SUMMARY** **CONSTRAIN**
- Locations Location **SUMMARY** **CONSTRAIN**
- Organism Organism **SUMMARY** **CONSTRAIN**
- Overlapping Features Sequence Feature **SUMMARY** **CONSTRAIN**
- Length Integer **SHOW** **CONSTRAIN**
- Name **SHOW** **CONSTRAIN**
- DB identifier **SHOW** **CONSTRAIN**
- Score Double **SHOW** **CONSTRAIN**
- Score Type **SHOW** **CONSTRAIN**
- Secondary Identifier **SHOW** **CONSTRAIN**
- Source **SHOW** **CONSTRAIN**
- Status **SHOW** **CONSTRAIN**
- Symbol **SHOW** **CONSTRAIN**

Query Overview

QTL

Qtl Id **X**

Trait **X**

= Residual Feed Intake **X** (A)

Organism Organism **X**

Name **X**

= Bos taurus **X** (B)

Overlapping Features Sequence Feature collection **X**

DB identifier **X**

Constraint logic: A and B

A and B

Figure 9

Manage Columns Manage Filters **A**

Showing 1 to 16 of 16 rows Rows per page: 10

SNP SNP rsID	SNP Reference Allele	SNP Alternate Allele
rs109137982		
rs109262355		

Manage Columns **B**

Selected Columns Sort Order

3 Columns Selected

Re-arrange or remove columns by dragging, or by using the buttons

- SNP - SNP rsID
- SNP - Reference Allele
- SNP - Alternate Allele

Manage Columns **C**

Selected Columns Sort Order

Choose a path from SNP

- Sequence
- Sequence Ontology Term
- Organism
- Chromosome Location
 - Strand
 - Do Not Compute Overlaps
 - Start
 - End
- Located On
 - Symbol
 - Name
 - Secondary Identifier
 - DB identifier
 - Organism
 - Synonyms
 - Data Sets
 - Locations

Manage Columns **D**

Selected Columns Sort Order

4 Columns Selected, 2 Removed

Re-arrange or remove columns by dragging, or by using the buttons

- SNP - SNP rsID
- Chromosome Location - Start
- Chromosome Location - End
- Located On - DB identifier

SNP - Reference Allele

SNP - Alternate Allele

Manage Columns Manage Filters

Showing 1 to 16 of 16 rows Rows per page: 10

SNP SNP rsID	Located On DB identifier	Chromosome Location Start	Chromosome Location End
rs109137982	GK000003.2	8308678	8308678
rs109262355	GK000020.2	35249040	35249040

E

Download results for query **F**

3 Columns

All Rows

No Compression

No Column Headers

Columns

- SNP > SNP rsID
- SNP > Chromosome Location > Located On > DB identifier
- SNP > Chromosome Location > Start
- SNP > Chromosome Location > End

Figure 10

Overlap features search from a new list of Genomic Regions

Search for features that overlap a list of genome coordinates you enter or upload, e.g. GK000001.2:50000..100000

- Genome regions in the following formats are accepted:
 - chromosome:start-end, e.g. GK000001.2:15000..25000
 - chromosome:start-end, e.g. GK000001.2:15000-25000
 - tab delimited
- Both base coordinate (e.g. BLAST, GFF/GFF3) and interbase coordinate (e.g. UCSC BED, Chado) systems are supported, users need to explicitly select one. By default, the base coordinate is selected.
- Each genome region needs to take a new line.

- Select Organism:
- Select Feature Types:
 - CDS
 - Copy Number Gain
 - Copy Number Loss
 - Copy Number Variation
 - Deletion
 - Exon
 - Gene
 - Indel
 - Inversion
 - miRNA
 - snRNA
 - Polypeptide
 - Primary Transcript
 - Probe
 - QTL
 - rRNA
 - Repeat Region
 - SNP
 - snRNA
 - tRNA
 - Tandem Duplication
 - Tandem Duplication Variant
 - Transcript
- Type/Paste in genomic regions (if base coordinate interbase coordinate)

(example for input format chr:1..1000)
 (example for input format chr:1-1000)
 (example for tab delimited input format)

or Upload genomic regions from a .txt file...
 Choose File
- Extend your regions at both sides:

20kb

Selected organism: *B. taurus*
 Selected feature types: SNP
 Extend Regions: 20 kbp

Export for all regions: or Create List by feature type: Page size: << First < Prev | Next > Last >>

GENOME REGION	FEATURE	FEATURE TYPE	LOCATION
GK000001.2:134110474..134150474 <input type="button" value="FASTA..."/> Original input: GK000001.2:134130474..134130474 <input type="button" value="TAB"/> <input type="button" value="CSV"/> <input type="button" value="GFF3"/> <input type="button" value="FASTA"/> <input type="button" value="BED"/> Create List by <input type="text" value="SNP"/> <input type="button" value="Go"/>	1437 SNP	records (too many to display all), please create a list	
GK000003.2:6610548..6650548 <input type="button" value="FASTA..."/> Original input: GK000003.2:6630548..6630548 <input type="button" value="TAB"/> <input type="button" value="CSV"/> <input type="button" value="GFF3"/> <input type="button" value="FASTA"/> <input type="button" value="BED"/> Create List by <input type="text" value="SNP"/> <input type="button" value="Go"/>	1481 SNP	records (too many to display all), please create a list	
GK000003.2:8288678..8328678 <input type="button" value="FASTA..."/> Original input: GK000003.2:8308678..8308678 <input type="button" value="TAB"/> <input type="button" value="CSV"/> <input type="button" value="GFF3"/> <input type="button" value="FASTA"/> <input type="button" value="BED"/> Create List by <input type="text" value="SNP"/> <input type="button" value="Go"/>	3335 SNP	records (too many to display all), please create a list	
GK000003.2:26573448..26613448 <input type="button" value="FASTA..."/> Original input: GK000003.2:26593448..26593448 <input type="button" value="TAB"/> <input type="button" value="CSV"/> <input type="button" value="GFF3"/> <input type="button" value="FASTA"/> <input type="button" value="BED"/> Create List by <input type="text" value="SNP"/> <input type="button" value="Go"/>	1511 SNP	records (too many to display all), please create a list	
GK000006.2:23031485..23071485 <input type="button" value="FASTA..."/> Original input: GK000006.2:23051485..23051485 <input type="button" value="TAB"/> <input type="button" value="CSV"/> <input type="button" value="GFF3"/> <input type="button" value="FASTA"/> <input type="button" value="BED"/> Create List by <input type="text" value="SNP"/> <input type="button" value="Go"/>	1806 SNP	records (too many to display all), please create a list	

Figure 11

Gene → Pathway ☆

Given a gene id or symbol, retrieve pathways. The pathway data sources retrieved may be affected by the input id (RefSeq, Ensembl or gene symbol).

Gene

LOOKUP: for Organism:

constrain to be saved Gene list

[web service URL](#) | [Perl](#) | [Python](#) | [Ruby](#) | [Java](#) [help] | [export XML](#)

Trail: Query

Gene → Pathway ☆

Given a gene id or symbol, retrieve pathways. The pathway data sources retrieved may be affected by the input id (RefSeq, Ensembl or gene symbol).

Manage Columns | Manage Filters | Manage Relationships | | |

Showing 1 to 25 of 38 rows | Rows per page: 25 | page 1

Gene Organism	Gene Gene ID	Gene Source	Gene Symbol	Pathways Identifier	Pathways Name
B. taurus	281039	RefSeq	CAST	R-BTA-1474228	Degradation of the extracellular matrix
B. taurus	281039	RefSeq	CAST	R-BTA-1474244	Extracellular matrix organization
B. taurus	327698	RefSeq	NDUFA2	R-BTA-1428517	The citric acid (TCA) cycle and respiratory electron transport
B. taurus	327698	RefSeq	NDUFA2	R-BTA-1430728	Metabolism
B. taurus	327698	RefSeq	NDUFA2	R-BTA-163200	Respiratory electron transport, ATP synthesis by chemiosmotic coupling
B. taurus	327698	RefSeq	NDUFA2	R-BTA-611105	Respiratory electron transport
B. taurus	327698	RefSeq	NDUFA2	R-BTA-6799198	Complex I biogenesis
B. taurus	327698	RefSeq	NDUFA2	bta:00190	Oxidative phosphorylation
B. taurus	327698	RefSeq	NDUFA2	bta:01100	Metabolic pathways

2 Data Set Names

Data Set Name	Count
Reactome pathways data set	26
KEGG pathways data set	12

Figure 13