

RESEARCH ARTICLE

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# Transcriptomes of *Frankia* sp. strain CcI3 in growth transitions

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## Abstract

**Background:** *Frankia* sp. strains are actinobacteria that form N<sub>2</sub>-fixing root nodules on angiosperms. Several reference genome sequences are available enabling transcriptome studies in *Frankia* sp. Genomes from *Frankia* sp. strains differ markedly in size, a consequence proposed to be associated with a high number of indigenous transposases, more than 200 of which are found in *Frankia* sp. strain CcI3 used in this study. Because *Frankia* exhibits a high degree of cell heterogeneity as a consequence of its mycelial growth pattern, its transcriptome is likely to be quite sensitive to culture age. This study focuses on the behavior of the *Frankia* sp. strain CcI3 transcriptome as a function of nitrogen source and culture age.

**Results:** To study global transcription in *Frankia* sp. CcI3 grown under different conditions, complete transcriptomes were determined using high throughput RNA deep sequencing. Samples varied by time (five days vs. three days) and by culture conditions (NH<sub>4</sub><sup>+</sup> added vs. N<sub>2</sub> fixing). Assembly of millions of reads revealed more diversity of gene expression between five-day and three-day old cultures than between three day old cultures differing in nitrogen sources. Heat map analysis organized genes into groups that were expressed or repressed under the various conditions compared to median expression values. Twenty-one SNPs common to all three transcriptome samples were detected indicating culture heterogeneity in this slow-growing organism. Significantly higher expression of transposase ORFs was found in the five-day and N<sub>2</sub>-fixing cultures, suggesting that N starvation and culture aging provide conditions for on-going genome modification. Transposases have previously been proposed to participate in the creating the large number of gene duplication or deletion in host strains. Subsequent RT-qPCR experiments confirmed predicted elevated transposase expression levels indicated by the mRNA-seq data.

**Conclusions:** The overall pattern of gene expression in aging cultures of CcI3 suggests significant cell heterogeneity even during normal growth on ammonia. The detection of abundant transcription of *nif* (nitrogen fixation) genes likely reflects the presence of anaerobic, N-depleted microsites in the growing mycelium of the culture, and the presence of significantly elevated transposase transcription during starvation indicates the continuing evolution of the *Frankia* sp. strain CcI3 genome, even in culture, especially under stressed conditions. These studies also sound a cautionary note when comparing the transcriptomes of *Frankia* grown in root nodules, where cell heterogeneity would be expected to be quite high.

## Background

Studies on actinorhizal symbioses have benefitted greatly from several genome sequences of the actinobacterial symbiont *Frankia* sp. strains. Such strains induce root nodules and fix N<sub>2</sub> in a broad array of plants [1]. The smallest frankial genome finished to date is that of

*Frankia* sp. HFPCcI3 (CcI3) that infects plants of the family Casuarinaceae; it is about 5.4 Mbp in size and encodes 4499 CDS [2]. A striking feature of the CcI3 genome is the presence of over 200 transposase genes or gene remnants that may play, or have played, a role in genome plasticity [3]. In addition, relative to other *Frankia* sp. genomes that have been sequenced, CcI3 contains few gene duplicates [2]. Comparative genome studies suggest that evolution has favored gene deletion rather than duplication in this strain, perhaps as an

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outcome of its symbiotic focus on a single, geographically limited group of plants in the Casuarinaceae [2].

Transcriptome sequencing of bacterial genomes has yielded surprising complexity (for a review see [4]). Such studies have shown differential cistron transcription within operons [5], small regulatory RNA transcripts [6-9] and numerous riboswitch controlled transcripts [10,11]. Significant transcriptional heterogeneity has also been found in single cultures that has been ascribed to subpopulations within an otherwise synchronized bacterial population [12]. High throughput RNA-seq methods provide a tool for transcript quantification with a much higher dynamic range than that provided by microarray studies by relying on direct comparison of transcript abundance for assessing differential expression [13].

*Frankia* transcriptome studies have the potential to reveal common genes and pathways active in, or essential to, symbiosis and free-living growth. A first step to resolving symbiotic-specific expression is to gain insight into transcriptional behavior and variability in axenic culture. This work helps address the issue of cultural heterogeneity that will likely be exacerbated by physiological heterogeneity in symbiosis. A previous transcriptome study has been done using whole-genome microarrays in *Alnus* and *Myrica* root nodules using cultured *Frankia alni* strain ACN14a as a reference [14]. In that study, relatively few surprises were encountered and the overall transcription profile was similar in both nodule types. We focus here on an approach using transcriptome deep sequencing of cultured *Frankia* strain CcI3 grown under different conditions, and the analysis of subsequent data to provide insight into the global expression that may impinge on physiology and genome stability in *Frankia* strains.

## Results and Discussion

### Culture characteristics and experimental design

As a consequence of its filamentous growth habit, *Frankia* sp. strain CcI3 grows from hyphal tips with an initial doubling time of about 18 hrs that subsequently slows to more linear growth [15]. As tips extend, cells left behind are physiologically in stationary phase and eventually senesce. Thus, even young cultures (defined here as three days old) have a degree of physiological heterogeneity that increases as cultures age [16]. This heterogeneity must be taken into account in interpreting global transcriptome analyses.

Several factors in our sampling and library creation may influence a transcriptome analysis. Single *Frankia* cultures were used in preparing RNA libraries for each sample prior to sequencing. In addition, each sample was run on the Illumina GA IIX sequencer without technical replicates. While technical and biological replicates

would have eliminated two potential sources of variability in the results of this experiment, several studies have suggested that both types of variability are unlikely to influence end results [13,17], while other studies have found significant variation among replicate samples [18,19]. Such effects may only influence low RPKM value genes [20] but, as with many such studies, our results must be viewed in the light of many potential variables.

### RNA sample quality and features

RNA preparations used for making dscDNA libraries for Illumina sequencing had 260/280 ratios greater than 2.0 and greater than 400 to 950 ng per  $\mu$ l. PCR amplification using primers for the *glnA* gene failed to yield an amplicon from RNA preparations indicating very low, if any, DNA contamination. In addition, an RT-PCR assay revealed no detectable DNA within total RNA samples prepared in a separate experiment, confirming that the RNA extraction technique can apply to sensitive RNA based experiments that use strain CcI3.

Transcriptome sequencing done using 5dNH4 CcI3 cells yielded about six million reads, three million of which could be mapped to the *Frankia* sp. CcI3 genome (Table 1). Almost 51% of the mapped reads were from rRNA or tRNA (Table 1). An updated base-calling algorithm (RTA v. 1.6) yielded substantially higher reads for samples from 3dNH4 and 3dN2 cultures. About 26 million reads were obtained for the latter samples, with about 16 million mapped reads in each (Table 1). Non-coding RNAs represented a greater proportion of mapped reads in these two samples, comprising nearly 80% of the total.

Even after ribosomal RNA depletion, non-coding sequences formed the majority of reads in all samples with the greatest reduction seen in the 5dNH4 sample (Table 1). This relative amount of rRNA could be related to the reduction of rRNA in older cultures, as observed in stationary and death phase cultures of *E. coli* [21]. On the other hand, given the concentration dependence of the rRNA depletion method used in preparing the mRNA-seq libraries, a decrease in the proportion of rRNA in the five-day time point could have resulted from more efficient depletion. Incomplete depletion of rRNA populations is similar to what is observed in other studies and is related to the sheer abundance of such sequences [22].

The number of coding RNA reads was similar among all three samples although the read length for the 3dNH4 and 3dN2 samples was 76 versus 34 for 5dNH4. All of the pseudogenes present in the CcI3 genome had transcripts in at least two of the three genomes (Table 1). Pseudogene transcription is presently not believed to be a rare event [23], though many pseudogenes identified

**Table 1 Dataset statistics**

	5dNH4 (#ORFs/#Reads <sup>‡</sup> )	3dNH4 (#ORFs/#Reads <sup>‡</sup> )	3dN2 (#ORFs/#Reads <sup>‡</sup> )
<b>rRNA/tRNA</b>	<b>65/1,401,120</b>	<b>65/12,799,049</b>	<b>64/13,524,803</b>
<b>mRNA</b>	<b>4,491/1,322,139</b>	<b>4,544/2,813,063</b>	<b>4544/2,945,205</b>
hypothetical	1,355/307,027	1,363/547,196	1,363/634,786
pseudogenes	49/8,882	49/31,566	49/44,989
transposases	135/24,528	137/62,484	137/87,928
phage proteins	26/12564	26/17,292	26/25,218
CRISPRs	9/6,553	9/8,926	9/12,702

<sup>‡</sup> Includes reads that mapped ambiguously. Ambiguous reads were only counted once.

in a bacterial genome may simply be misannotated ORFs.

### Functional Pathways

The 100 genes with the highest RPKM value in each condition, omitting ribosomal RNAs, are listed in Table 2. The number of hypothetical genes in this group range from 29 in the 3dNH4 cells to 39 in the 3dN2 cells to 43 in the 5dNH4 cells. Older cultures had more transcripts associated with tRNAs, transposases, CRISPR elements, integrases and hypothetical proteins than did younger cultures. Indeed, had they been included in the list, 18 of the 46 tRNA genes in CcI3 would have been in the top 100 most abundant transcript populations in 5dNH4 cells whereas no tRNAs were found in the top 100 transcripts in 3dN2 or 3dNH4 cell populations. The picture painted by the abundance of such transcripts is one of cells starved for essential metabolites such as amino acids, as expected in aging cells. In addition, enzymes involved in solving oxidative damage (e.g. protein-methionine-S-oxide reductase) were also more abundant in the older culture. Conversely, enzymes involved in catabolism (eg. alcohol dehydrogenase) were more frequently represented in the two younger cultures.

Comparison of the top 100 gene lists with each other (color coded in Table 2) and construction of heat maps of all genes revealed that overall gene expression varied more with culture age (three versus five days) than culture condition (+/- NH<sub>4</sub><sup>+</sup>), with 3dNH4 and 3dN2 clustering before the 5dNH4 sample (Figure 1). Gene dendrograms (left side of the figure) gave five clusters of genes (Groups I through V) that had within-group expression profiles consistent among the three culture conditions tested. The genes in each cluster are listed in Additional File 1: Gene\_list.xls.

Group I genes are clearly down-regulated in 3dNH4 cells; these include 30 transporter related genes, five diguanylate cyclases and an array of putative N-controlled proteins such as assimilatory nitrate reductase, adenosine deaminase, allantoinase and nitrogen fixation (*nif*) genes in addition to 252 hypothetical proteins.

Group II genes are up regulated in 3dN2 cultures and include most of the *nif* genes, genes involved in sulfur metabolism and iron-sulfur protein synthesis, cell division proteins and hydrogenase synthesis. The 3dN2 culture was prepared with a modified iron stock containing a higher concentration of iron sulphate and sodium molybdate [24]. We cannot rule out that an increase in iron-sulfur protein synthesis may be related to the increase in iron sulphate to the medium although it is more likely to be related to an increased demand for iron and molybdenum. Eight phage integrases were also present in Group II, which was the highest number of integrases present in any of the five groups. Group III contains genes that have relatively more transcripts in 5dNH4 cells; these include a larger proportion of hypothetical protein ORFs (523 ORFs) than were present in the other four groups (average of ~200 ORFs per group). All of the annotated excisionase/Xis ORFs were present in the Group III list, suggesting that phage-related excisionases are being transcribed more in the 5dNH4 sample than in the other conditions. Group IV genes were more abundantly transcribed in the 3dNH<sub>4</sub><sup>+</sup> sample including several sigma factors; this group also had the fewest transposase ORFs (2 ORFs). Group V contains ORFs more highly expressed in younger cultures. ORFs in this grouping include 17 ribosomal protein ORFs, and a majority of the glycolytic enzymes.

As expected, *nif* ORFs were more highly expressed in the 3dN2 sample, with numerous vesicles present, than in the 3dNH4 sample and were in Group II on the heat map. The 5dNH4 culture also had *nif* expression above that detected in the 3dNH4 culture. Three *nif* ORFs were not significantly expressed in the 5dNH4 sample over the 3dNH4 sample as predicted by a Kal's ztest p value [25] (Table 3). On the other hand, the genes for the core nitrogenase components nitrogenase reductase (*nifH*), and nitrogenase alpha and beta chains (*nifKD*) were upregulated in the 3dN2 sample, and were cotranscribed to similar extents within individual cultures, suggesting that they exist in an operon independent from the rest of the *nif* cluster. An intergenic space consisting

**Table 2 The top 100 highly expressed coding ORFs predicted by RPKM values**

3dNH4 <sup>1</sup>	Locus tag	RPKM <sup>2</sup>	3dN2	Locus tag	RPKM	5dNH4	Locus tag	RPKM
heat shock protein Hsp20	<a href="#">Francci3_1179</a>	<b>10755</b>	heat shock protein Hsp20	<a href="#">Francci3_1179</a>	<b>3553</b>	hypothetical protein	<a href="#">Francci3_1017</a>	4967
aldehyde dehydrogenase	<a href="#">Francci3_2944</a>	<b>7165</b>	aldehyde dehydrogenase	<a href="#">Francci3_2944</a>	<b>3152</b>	heat shock protein Hsp20	<a href="#">Francci3_1179</a>	<b>2077</b>
chaperonin GroEL	<a href="#">Francci3_4398</a>	<b>5923</b>	hypothetical protein	<a href="#">Francci3_1545</a>	<b>2327</b>	hypothetical protein	<a href="#">Francci3_3999</a>	<b>1926</b>
<u>cold-shock DNA-binding</u>	<a href="#">Francci3_0260</a>	<u>5495</u>	<b>transposase IS66</b>	<a href="#">Francci3_1864</a>	<b>2261</b>	<b>transposase IS66</b>	<a href="#">Francci3_1864</a>	<b>1801</b>
<u>OsmC-like protein</u>	<a href="#">Francci3_4465</a>	<u>5490</u>	<u>hypothetical protein</u>	<a href="#">Francci3_2178</a>	<u>1993</u>	polysaccharide deacetylase	<a href="#">Francci3_0165</a>	1616
<u>co-chaperonin GroES</u>	<a href="#">Francci3_0632</a>	<u>5362</u>	response regulator receiver	<a href="#">Francci3_0120</a>	1823	hypothetical protein	<a href="#">Francci3_2101</a>	1596
<u>Hemerythrin HHE cation</u>	<a href="#">Francci3_1066</a>	<u>4392</u>	<u>Hemerythrin HHE cation</u>	<a href="#">Francci3_1066</a>	<u>1807</u>	phage integrase	<a href="#">Francci3_4274</a>	1451
<b>hypothetical protein</b>	<a href="#">Francci3_1545</a>	<b>4225</b>	<u>hypothetical protein</u>	<a href="#">Francci3_1936</a>	<u>1789</u>	Radical SAM	<a href="#">Francci3_1753</a>	1392
<u>NAD/NADP transhydrogenase</u>	<a href="#">Francci3_2947</a>	<u>3226</u>	<u>OsmC-like protein</u>	<a href="#">Francci3_4465</a>	<u>1777</u>	hypothetical protein	<a href="#">Francci3_2241</a>	1333
<b>UspA</b>	<a href="#">Francci3_2760</a>	<b>3221</b>	<b>hypothetical protein</b>	<a href="#">Francci3_3999</a>	<b>1614</b>	hypothetical protein	<a href="#">Francci3_2890</a>	1265
<u>hypothetical protein</u>	<a href="#">Francci3_3494</a>	<u>3190</u>	<u>cold-shock DNA-binding</u>	<a href="#">Francci3_0260</a>	<u>1592</u>	phosphoribosyl-ATPphosphatase	<a href="#">Francci3_4317</a>	1245
<u>hypothetical protein</u>	<a href="#">Francci3_2178</a>	<u>3071</u>	<u>sigma 54 modulation</u>	<a href="#">Francci3_0764</a>	<u>1574</u>	hypothetical protein	<a href="#">Francci3_0159</a>	1184
<u>sigma 54 modulation protein</u>	<a href="#">Francci3_0764</a>	<u>3004</u>	<u>cold-shock DNA-binding</u>	<a href="#">Francci3_4469</a>	<u>1458</u>	ribonucleaseHIII	<a href="#">Francci3_3588</a>	1161
<u>cold-shock DNA-binding</u>	<a href="#">Francci3_4469</a>	<u>2949</u>	<u>putative DNA-binding</u>	<a href="#">Francci3_1949</a>	<u>1392</u>	GDP-mannose 4,6-dehydratase	<a href="#">Francci3_1307</a>	1134
<u>Alcohol dehydrogenase</u>	<a href="#">Francci3_2945</a>	<u>2916</u>	<u>LuxR family regulator</u>	<a href="#">Francci3_0765</a>	<u>1361</u>	hypothetical protein	<a href="#">Francci3_4023</a>	1122
<u>putative Lsr2-like protein</u>	<a href="#">Francci3_3498</a>	<u>2659</u>	<b>chaperoninGroEL</b>	<a href="#">Francci3_4398</a>	<b>1199</b>	major facilitator superfamily	<a href="#">Francci3_2289</a>	1122
<u>hypothetical protein</u>	<a href="#">Francci3_1936</a>	<u>2577</u>	hypothetical protein	<a href="#">Francci3_4123</a>	1176	RNA-directed DNA polymerase	<a href="#">Francci3_2318</a>	1088
<u>hypothetical protein</u>	<a href="#">Francci3_2270</a>	<u>2529</u>	<u>hypothetical protein</u>	<a href="#">Francci3_3494</a>	<u>1175</u>	methionine-S-oxide reductase	<a href="#">Francci3_2268</a>	1071
<u>thioredoxin-related</u>	<a href="#">Francci3_0447</a>	<u>2355</u>	<u>hypothetical protein</u>	<a href="#">Francci3_2269</a>	<u>1174</u>	HypA	<a href="#">Francci3_1937</a>	1047
<b>SsgA</b>	<a href="#">Francci3_3418</a>	<b>2154</b>	<u>transcriptional regulator</u>	<a href="#">Francci3_4255</a>	<u>1167</u>	acyltransferase 3	<a href="#">Francci3_2337</a>	987
<u>luciferase-like</u>	<a href="#">Francci3_2761</a>	<u>2117</u>	<u>co-chaperoninGroES</u>	<a href="#">Francci3_0632</a>	<u>1150</u>	hypothetical protein	<a href="#">Francci3_3302</a>	982
<u>molecular chaperone DnaK</u>	<a href="#">Francci3_4352</a>	<u>2036</u>	hypothetical protein	<a href="#">Francci3_2442</a>	1117	Serine acetyltransferase-like	<a href="#">Francci3_3842</a>	970
<u>globin</u>	<a href="#">Francci3_2581</a>	<u>1935</u>	<b>SsgA</b>	<a href="#">Francci3_3418</a>	<b>1043</b>	<b>hypothetical protein</b>	<a href="#">Francci3_0227</a>	<b>970</b>
<u>LuxR family regulator</u>	<a href="#">Francci3_0765</a>	<u>1934</u>	<u>SecE subunit</u>	<a href="#">Francci3_0567</a>	<u>1037</u>	hypothetical protein	<a href="#">Francci3_1719</a>	965
<u>thioredoxin reductase</u>	<a href="#">Francci3_4536</a>	<u>1913</u>	<u>putative Lsr2-like protein</u>	<a href="#">Francci3_3498</a>	<u>1022</u>	hypothetical protein	<a href="#">Francci3_0238</a>	957
<u>Rhodanese-like</u>	<a href="#">Francci3_0449</a>	<u>1881</u>	<u>PEP phosphomutase</u>	<a href="#">Francci3_1533</a>	<u>1005</u>	hypothetical protein	<a href="#">Francci3_2200</a>	947
<u>carbonic anhydrase</u>	<a href="#">Francci3_0708</a>	<u>1859</u>	<u>hypothetical protein</u>	<a href="#">Francci3_2270</a>	<u>973</u>	hypothetical protein	<a href="#">Francci3_1831</a>	945
<b>superfamily MFS_1</b>	<a href="#">Francci3_2752</a>	<b>1811</b>	chaperone hypC/hupF	<a href="#">Francci3_1946</a>	954	serine/threonine kinase	<a href="#">Francci3_4051</a>	938
<u>hypothetical protein</u>	<a href="#">Francci3_3250</a>	<u>1807</u>	transposase, IS4	<a href="#">Francci3_3990</a>	953	signal transduction kinase	<a href="#">Francci3_0085</a>	938
<u>exodeoxyribonuclease III</u>	<a href="#">Francci3_1180</a>	<u>1754</u>	<u>thioredoxin-related</u>	<a href="#">Francci3_0447</a>	<u>951</u>	hypothetical protein	<a href="#">Francci3_4019</a>	922
<u>PEP phosphomutase</u>	<a href="#">Francci3_1533</a>	<u>1742</u>	<u>ATP synthase F0</u>	<a href="#">Francci3_3713</a>	<u>928</u>	hypothetical protein	<a href="#">Francci3_0396</a>	914
<u>STAS (anti-σ factor antagonist)</u>	<a href="#">Francci3_0441</a>	<u>1728</u>	mannose 4,6-dehydratase	<a href="#">Francci3_1053</a>	921	CRISPR-associated protein	<a href="#">Francci3_0021</a>	899
<u>hypothetical protein</u>	<a href="#">Francci3_1935</a>	<u>1687</u>	phage integrase	<a href="#">Francci3_4338</a>	919	hypothetical protein	<a href="#">Francci3_0038</a>	899
sigma 38	<a href="#">Francci3_3505</a>	1673	protein of unknown function	<a href="#">Francci3_3347</a>	892	Recombinase	<a href="#">Francci3_3989</a>	898
<b>hypothetical protein</b>	<a href="#">Francci3_0227</a>	<b>1665</b>	transposase, IS4	<a href="#">Francci3_0391</a>	878	aldo/keto reductase	<a href="#">Francci3_3416</a>	890
<u>hypothetical protein</u>	<a href="#">Francci3_1615</a>	<u>1634</u>	<b>major facilitator MFS_1</b>	<a href="#">Francci3_2752</a>	<b>865</b>	transposase, IS4	<a href="#">Francci3_1873</a>	875
<u>hypothetical protein</u>	<a href="#">Francci3_2943</a>	<u>1629</u>	<u>NAD/NADP transhydrogenase</u>	<a href="#">Francci3_2947</a>	<u>863</u>	Excisionase/Xis, DNA-binding	<a href="#">Francci3_0405</a>	875
<u>hypothetical protein</u>	<a href="#">Francci3_0054</a>	<u>1629</u>	hypothetical protein	<a href="#">Francci3_4084</a>	855	transposase, IS4	<a href="#">Francci3_0151</a>	874

**Table 2 The top 100 highly expressed coding ORFs predicted by RPKM values (Continued)**

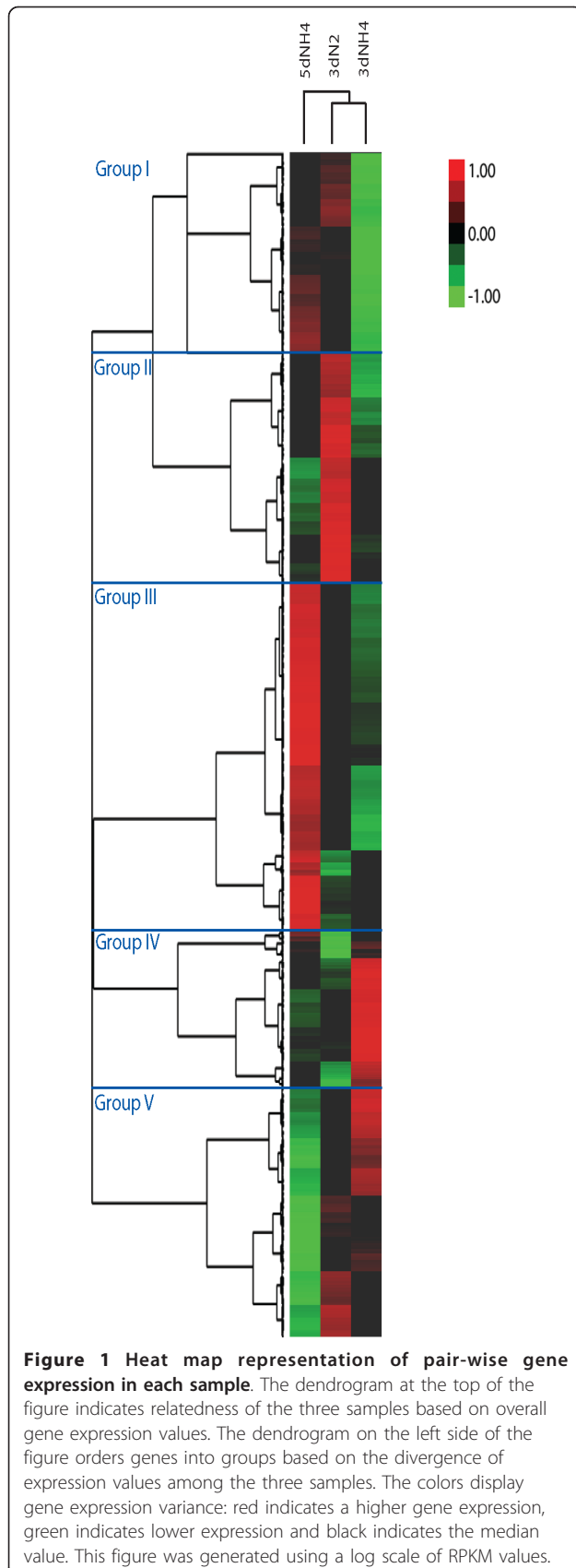
<b>transposase IS66</b>	<b>Francci3_1864</b>	<b>1625</b>	<i>hypothetical protein</i>	<i>Francci3_2380</i>	839	CRISPR-associated protein	<i>Francci3_0020</i>	869
<u>transcriptional regulator, CarD</u>	<u>Francci3_4255</u>	<u>1596</u>	<i>hypothetical protein</i>	<i>Francci3_4114</i>	821	<i>CRISPR-associated protein</i>	<i>Francci3_3345</i>	863
alanine dehydrogenase/PNT-like	Francci3_2946	1532	<u>Alcohol dehydrogenase</u>	<u>Francci3_2945</u>	<u>796</u>	glycosyl transferase	<i>Francci3_3318</i>	859
<u>serine phosphatase</u>	<u>Francci3_3249</u>	<u>1453</u>	<u>hypothetical protein</u>	<u>Francci3_3791</u>	<u>782</u>	metallophosphoesterase	<i>Francci3_1990</i>	839
chaperonin GroEL	Francci3_0633	1439	<u>acyl-CoA dehydrogenase</u>	<u>Francci3_1000</u>	<u>781</u>	<i>hypothetical protein</i>	<i>Francci3_3339</i>	837
<u>hypothetical protein</u>	<u>Francci3_0949</u>	<u>1437</u>	<i>transcriptional regulator</i>	<i>Francci3_3081</i>	780	<i>transcriptional regulator</i>	<i>Francci3_3081</i>	834
<u>transcription factor WhiB</u>	<u>Francci3_3759</u>	<u>1430</u>	<i>hypothetical protein</i>	<i>Francci3_0037</i>	779	<i>hypothetical protein</i>	<i>Francci3_3317</i>	826
fatty acid desaturase, type 2	Francci3_0307	1430	Amino acid adenylation	<i>Francci3_2461</i>	777	<i>hypothetical protein</i>	<i>Francci3_4072</i>	824
STAS	Francci3_4302	1405	<i>hypothetical protein</i>	<i>Francci3_1615</i>	775	transcriptional regulator	<i>Francci3_0908</i>	816
Heavy metal transportprotein	Francci3_0489	1368	<i>hypothetical protein</i>	<i>Francci3_2179</i>	775	<i>hypothetical protein</i>	<i>Francci3_4129</i>	809
sigma-24	Francci3_3768	1353	<u>hypothetical protein</u>	<u>Francci3_1534</u>	<u>773</u>	transposase, IS4	<i>Francci3_4227</i>	803
transcriptional regulator, TetR	Francci3_2758	1349	<i>hypothetical protein</i>	<i>Francci3_2329</i>	767	<b>Antibiotic biosynthesis</b>	<b>Francci3_0875</b>	<b>800</b>
<u>hypothetical protein</u>	<u>Francci3_3417</u>	<u>1343</u>	<u>carbonic anhydrase</u>	<u>Francci3_0708</u>	<u>764</u>	<i>hypothetical protein</i>	<i>Francci3_3336</i>	796
<u>SecE subunit</u>	<u>Francci3_0567</u>	<u>1339</u>	<u>transcription factor WhiB</u>	<u>Francci3_3759</u>	<u>751</u>	<i>hypothetical protein</i>	<i>Francci3_2440</i>	781
Excisionase/Xis, DNA-binding	Francci3_0099	1327	<b>UspA</b>	<b>Francci3_2760</b>	<b>747</b>	<i>hypothetical protein</i>	<i>Francci3_4509</i>	778
<u>hypothetical protein</u>	<u>Francci3_3791</u>	<u>1315</u>	<u>exodeoxyribonuclease III</u>	<u>Francci3_1180</u>	<u>747</u>	putative copper resistance	<i>Francci3_2497</i>	771
<u>ATP synthase FO, A subunit</u>	<u>Francci3_3713</u>	<u>1263</u>	<i>hypothetical protein</i>	<i>Francci3_1832</i>	737	transcriptional regulator	<i>Francci3_0210</i>	765
30S ribosomal proteinS1	Francci3_1057	1256	<u>protein of unknown function</u>	<u>Francci3_2628</u>	<u>714</u>	<i>hypothetical protein</i>	<i>Francci3_1090</i>	764
heat shock protein Hsp20	Francci3_2174	1241	<i>hypothetical protein</i>	<i>Francci3_4509</i>	714	<i>hypothetical protein</i>	<i>Francci3_4156</i>	760
NAD(P) transhydrogenase, beta	Francci3_2948	1231	<i>hypothetical protein</i>	<i>Francci3_1650</i>	709	RNA-binding S4	<i>Francci3_3479</i>	747
<u>putative transcriptional regulator</u>	<u>Francci3_1674</u>	<u>1218</u>	STAS	<u>Francci3_0441</u>	<u>701</u>	<b>hypothetical protein</b>	<b>Francci3_1545</b>	<b>746</b>
protein of unknown function	Francci3_0450	1215	<u>molecularchaperoneDnaK</u>	<u>Francci3_4352</u>	<u>694</u>	<i>hypothetical protein</i>	<i>Francci3_3238</i>	746
<u>Alcohol dehydrogenase</u>	<u>Francci3_1544</u>	<u>1206</u>	<i>hypothetical protein</i>	<i>Francci3_0159</i>	693	<i>hypothetical protein</i>	<i>Francci3_3301</i>	737
<u>putative DNA-binding protein</u>	<u>Francci3_1949</u>	<u>1203</u>	<u>acyl transferase region</u>	<u>Francci3_0991</u>	<u>691</u>	<i>hypothetical protein</i>	<i>Francci3_1985</i>	724
glutaredoxin 2	Francci3_0483	1202	regulatory protein GntR	<i>Francci3_3218</i>	690	<u>Rhodanese-like</u>	<u>Francci3_2753</u>	<u>721</u>
translation elongation factor Tu	Francci3_0580	1179	CRISPR-associated protein	<i>Francci3_3346</i>	680	Thiolase	<i>Francci3_2502</i>	718
<u>thioredoxin</u>	<u>Francci3_4537</u>	<u>1165</u>	<i>hypothetical protein</i>	<i>Francci3_1874</i>	678	response regulator receiver	<i>Francci3_0120</i>	715
cytochrome P450	Francci3_4464	1164	<u>hypothetical protein</u>	<u>Francci3_1935</u>	<u>672</u>	<i>hypothetical protein</i>	<i>Francci3_0498</i>	705
<i>hypothetical protein</i>	Francci3_2582	1156	IS630 family transposase	<i>Francci3_1872</i>	670	DNApolymerasellsubunitalpha	<i>Francci3_4168</i>	703
<u>hypothetical protein</u>	<u>Francci3_1534</u>	<u>1106</u>	<u>globin</u>	<u>Francci3_2581</u>	<u>663</u>	<i>hypothetical protein</i>	<i>Francci3_0037</i>	693
<u>protein of unknown function</u>	<u>Francci3_1406</u>	<u>1054</u>	<i>hypothetical protein</i>	<i>Francci3_4127</i>	657	<i>hypothetical protein</i>	<i>Francci3_3241</i>	684
Vesicle-fusing ATPase	Francci3_2630	1041	<u>thioredoxin</u>	<u>Francci3_4537</u>	<u>653</u>	30SribosomalproteinS6	<i>Francci3_4522</i>	683
HesB/YadR/YfhF	Francci3_3121	1032	<i>hypothetical protein</i>	<i>Francci3_0066</i>	644	putative hydrolase	<i>Francci3_2567</i>	682
<i>hypothetical protein</i>	Francci3_0532	1022	<u>Alcohol dehydrogenase</u>	<u>Francci3_1544</u>	<u>644</u>	<i>transposase IS116/IS110</i>	<i>Francci3_2124</i>	681
<u>acyl transferase region</u>	<u>Francci3_0991</u>	<u>1015</u>	<i>hypothetical protein</i>	<i>Francci3_2440</i>	642	<i>hypothetical protein</i>	<i>Francci3_1807</i>	675
Superoxide dismutase	Francci3_2817	1013	Tetratricopeptide TPR_4	<i>Francci3_1951</i>	639	<i>hypothetical protein</i>	<i>Francci3_1805</i>	675
<i>hypothetical protein</i>	Francci3_2185	1007	<b>hypothetical protein</b>	<b>Francci3_0227</b>	<b>635</b>	<i>hypothetical protein</i>	<i>Francci3_2364</i>	675
<i>hypothetical protein</i>	Francci3_4343	1006	<i>hypothetical protein</i>	<i>Francci3_2315</i>	634	<i>hypothetical protein</i>	<i>Francci3_2380</i>	671
<u>serine/threonine kinase</u>	<u>Francci3_4051</u>	<u>989</u>	<i>hypothetical protein</i>	<i>Francci3_4019</i>	633	response regulator receiver	<i>Francci3_4048</i>	670

**Table 2 The top 100 highly expressed coding ORFs predicted by RPKM values (Continued)**

<u>acyl-CoA dehydrogenase</u>	<u>Francci3_1000</u>	<u>989</u>	<u>hypothetical protein</u>	<u>Francci3_0949</u>	<u>633</u>	putative O-methyltransferase	Francci3_0204	670
conserved hypothetical protein	Francci3_0096	986	<u>serine phosphatase</u>	<u>Francci3_3249</u>	<u>632</u>	channel protein	Francci3_3898	669
hypothetical protein	Francci3_3886	983	Amino acid adenylation	Francci3_2459	632	hypothetical protein	Francci3_2032	667
<u>Rhodanese-like</u>	<u>Francci3_2753</u>	<u>982</u>	<i>transposase IS116/IS110</i>	<i>Francci3_2124</i>	630	hypothetical protein	Francci3_1459	664
hypothetical protein	Francci3_4042	973	<u>hypothetical protein</u>	<u>Francci3_3417</u>	<u>628</u>	flavoprotein	Francci3_1816	662
<b>hypothetical protein</b>	<b>Francci3_3999</b>	<b>971</b>	<b>Antibiotic biosynthesis</b>	<b>Francci3_0875</b>	<b>626</b>	hypothetical protein	Francci3_0160	660
<u>protein of unknown function</u>	<u>Francci3_2628</u>	<u>958</u>	<u>protein of unknown function</u>	<u>Francci3_1406</u>	<u>621</u>	AMP-dependent synthetase	Francci3_1806	659
<u>LuxR family regulator</u>	<u>Francci3_3253</u>	<u>958</u>	hypothetical protein	Francci3_3247	621	serine/threonine protein kinase	Francci3_3395	659
50SribosomalproteinL24	Francci3_0593	944	<u>hypothetical protein</u>	<u>Francci3_2943</u>	<u>620</u>	hypothetical protein	Francci3_4161	655
ribosomal protein S2	Francci3_3581	936	transcription factor WhiB	Francci3_3790	618	hypC/hupF	Francci3_1946	655
hypothetical protein	Francci3_2736	934	hypothetical protein	Francci3_3997	618	hypothetical protein	Francci3_0494	655
<u>hypothetical protein</u>	<u>Francci3_2269</u>	<u>932</u>	transcriptional regulator	Francci3_4158	614	transcriptional regulator	Francci3_0985	654
hypothetical protein	Francci3_2809	929	hypothetical protein	Francci3_2184	610	Excisionase/Xis, DNA-binding	Francci3_1856	653
acyl-CoA dehydrogenase-like	Francci3_0053	915	<u>hypothetical protein</u>	<u>Francci3_0054</u>	<u>608</u>	phosphohydrolase	Francci3_1134	648
<b>Antibiotic biosynthesis</b>	<b>Francci3_0875</b>	<b>911</b>	CRISPR-associated protein	Francci3_0023	608	<b>SsgA</b>	<b>Francci3_3418</b>	<b>646</b>
2-oxoacid oxidoreductase	Francci3_3248	906	Recombinase	Francci3_2373	607	<b>major facilitator MFS_1</b>	<b>Francci3_2752</b>	<b>643</b>
translationinitiationfactorIF-1	Francci3_0605	904	<i>CRISPR-associated protein</i>	<i>Francci3_3345</i>	606	Inorganic diphosphatase	Francci3_4310	636
electron transfer flavoprotein	Francci3_3659	889	hypothetical protein	Francci3_2219	606	hypothetical protein	Francci3_1032	636
hypothetical protein	Francci3_4326	884	hypothetical protein	Francci3_3299	605	DNA-directed RNA polymerase	Francci3_3194	635
50SribosomalproteinL33	Francci3_0563	880	<u>LuxR family regulator</u>	<u>Francci3_3253</u>	<u>604</u>	<b>chaperoninGroEL</b>	<b>Francci3_4398</b>	<b>635</b>
hypothetical protein	Francci3_3625	856	<i>hypothetical protein</i>	<i>Francci3_2101</i>	604	<b>UspA</b>	<b>Francci3_2760</b>	<b>633</b>
Cytochrome-c oxidase	Francci3_2009	855	<u>transcriptional regulator</u>	<u>Francci3_1674</u>	<u>600</u>	<b>Aldehyde dehydrogenase</b>	<b>Francci3_2944</b>	<b>632</b>
GrpE protein	Francci3_4353	846	<i>transcriptional regulator</i>	<i>Francci3_0908</i>	596	hypothetical protein	Francci3_1014	631

<sup>1</sup> Gene annotations and locus tag numbers are colored based on their presence in all three samples (bold), in the 3dN2 and 5dNH4 samples (italic), in the 3dN2 and 3dNH4 samples (underscore), in the 3dNH4 and 5dNH4 samples (italic/underscore), and in one of the three samples (normal font).

<sup>2</sup> RPKM (Reads per Kilobase Million) = (# reads per ORF)/(size of ORF in kilobases × millions of reads in the dataset).



of 208 nucleotides between these three ORFs and the rest of the cluster supports this analysis. The presence of *nif* transcripts in all cell types, even where ammonia should still be in excess, is in concert with the heterogeneous nature of the frankial growth habit, where mycelia develop microsites that are potentially nutrient deficient or microaerobic due to adjoining cell populations. The 5dNH4 cells are most likely depleted for combined nitrogen and, indeed, a few vesicles can be observed in older cultures. This observation highlights a fundamental problem with the mRNA deep sequencing of a *Frankia* culture where different cell physiologies can skew average gene expression in a culture. Apart from isolated vesicles [26] that are unlikely to give a sufficient quantity of mRNA for second generation sequencing technologies, long-read, single molecule sequencing techniques run in parallel could specifically sequence the transcriptome of distinct cell morphologies in a pure culture as was recently done with *Vibrio cholerae* [27].

#### Insertion Sequences

Recent studies on *Frankia* proteomes have indicated the presence of several transposases in CcI3 grown in culture and in symbiosis [28], raising the question of how IS elements behave in cultured CcI3 cells. Given the number of transposase ORFs in the CcI3 genome (148 complete plus 53 fragments identified by PSI-BLAST analysis [2]), mRNA deep sequencing provides an efficient method of quantifying their behavior in cultures grown under different conditions.

RPKM values for the transposase ORFs were plotted against the locations of IS elements in strain CcI3 (Figure 2; [3]). Additional files 2, 3, 4, 5, 6 and 7 list the calculated expression data for the transposase ORFs. Transposase transcripts were generally more abundant than the transcriptome's median RPKM value (dashed line; values respective of sample) throughout the genome. The visual representation of transcript abundance in Figure 2 indicates that transposase ORFs were overall more highly expressed in older cultures and, to a lesser extent, in  $N_2$  fixing cells than in younger, nutrient sufficient cultures. Seventy-three transposase ORFs in the 5dNH4 sample were more highly expressed with respect to the 3dNH4 sample (Figure 2; Additional file 8: SNP\_call\_list.xls). Only 29 transposase ORFs were shown statistically to have higher expression in 3dNH4 than in 5dNH4. A similar trend was noticed in the 3dN2 vs 3dNH4 sample, with 91 transposase ORFs having statistically significant higher expression values in the 3dN2 sample. Many transposase ORFs had similar expression in the 3dN2 vs 3dNH4 and the 5dNH4 vs 3dNH4 comparisons. This is reflected in the *z*test *p* values, as the 3dN2 vs 3dNH4 comparison had 50 changes with *p* values greater than 0.05 and the 5dNH4

**Table 3 Fold changes of *nif* cluster ORF expression levels<sup>1</sup>**

Feature ID	Annotation	5dNH4 vs 3dNH4	3dN2 vs 3dNH4	3dN2 vs 5dNH4
Francci3_4473	thiamine pyrophosphate enzyme-like TPP-binding	1.28	1.89	1.48
Francci3_4474	pyruvate flavodoxin/ferredoxin oxidoreductase-like	1.60	1.93	1.20
Francci3_4475	aminotransferase, class V	2.90	1.52	0.90
Francci3_4476	UBA/THIF-type NAD/FAD binding fold	1.20*	2.08	1.73
Francci3_4477	HesB/YadR/YfhF	2.09	2.00	0.04
Francci3_4478	nitrogenase cofactor biosynthesis protein NifB	1.35	2.17	1.61
Francci3_4479	NifZ	0.54	1.45	2.23
Francci3_4480	nitrogen fixation protein NifW	2.49	2.14	0.16*
Francci3_4481	protein of unknown function DUF683	2.81	1.75	0.61
Francci3_4482	protein of unknown function DUF269	0.23*	1.44	1.77
Francci3_4483	Dinitrogenase iron-molybdenum cofactor biosynthesis	1.82	2.03	1.12*
Francci3_4484	nitrogenase molybdenum-iron cofactor biosynthesis protein NifN	2.55	1.78	0.43
Francci3_4485	nitrogenase MoFe cofactor biosynthesis protein NifE	1.47	1.92	1.31
Francci3_4486	nitrogenase molybdenum-iron protein beta chain	1.16*	2.40	2.08
Francci3_4487	nitrogenase molybdenum-iron protein alpha chain	1.62	2.94	1.82
Francci3_4488	nitrogenase iron protein	1.34	3.71	2.77

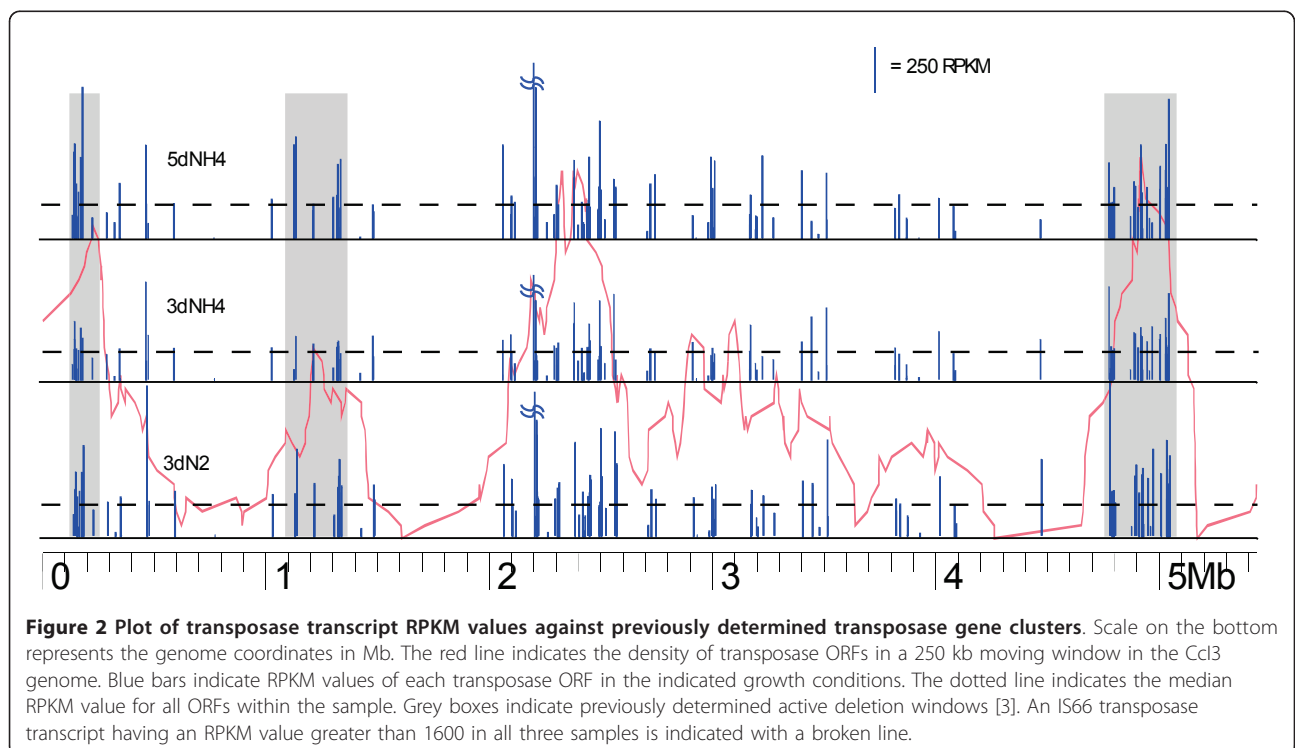
<sup>1</sup>Fold changes calculated as quotients of RPKM values

\* Insignificant p value as determined by Kal's ztest.

versus 3dNH4 comparison had 48 changes with p values greater than 0.05. The majority of the insignificant p values in the comparisons are due to similarity of RPKM values.

One IS66 transposase (Locus tag: Francci3\_1864) near the 2 Mb region of the genome had an RPKM greater than 1600 in all samples. The majority of these reads

were ambiguous. This transposase has five paralogs with greater than 99% nucleotide similarity, thereby accounting for ambiguous reads, so the elevated RPKM, while still high, is distributed among several paralogs. Other transposase ORFs with RPKM values higher than the median were more likely to be present in Cci3 deletion windows (gray boxes [3]) as determined by a Chi Square





test against the likelihood that high RPKM transposase ORFs would exist in a similar sized region of the genome at random ( $p$  value =  $1.32 \times 10^{-7}$ ). This observation suggests that any transposase found in these windows is more likely to be transcribed at higher levels than transposases outside of these regions.

The largest change in expression was found in an IS3/IS911 ORF between the 5dNH4 and 3dNH4 samples. This ORF (locus tag: Francci3\_1726, near 1.12 Mb) was expressed eleven fold higher in the 5dNH4 sample than in the 3dNH4 sample. Five other IS66 ORFs are also highly expressed in 5dNH4 ranging from 4 fold to 5 fold higher expression than in the 3dNH4 sample. Eight IS4 transposases had no detected reads under the alignment conditions in each growth condition. These eight IS4 transposases are members of a previously described group of 14 paralogs that have nearly 99% similarity in nucleic acid sequence [3]. Parameters of the sequence alignment used allowed for ten sites of ambiguity, therefore discarding reads from eight of these 14 duplicates as too ambiguous to map on the reference genome. Graphic depictions of assembled reads derived from raw CLC workbench files show that the majority of reads for the six detected IS4 transposases mapped around two regions. Both of these regions contained one nucleotide difference from the other eight identical transposases. *De novo* alignment of the unmapped reads from each sample resulted in a full map of the highly duplicated IS4 transposase ORFs (data not shown).

More globally, the 5dNH4 and 3dN2 samples had higher RPKM values per transposase ORF than in the 3dNH4 sample. The sum of the RPKM values among the transposase data set placed the 5dNH4 sample (34350 sum RPKM) and the 3dN2 (36150 sum RPKM) each nearly 30% higher than in 3dNH4 (26916 sum RPKM). The numbers of transposase genes classified as upregulated in the heat maps in Figure 1 include 44 in 3dN2 cells, 40 in 5dNH4 cells and only two in 3dNH4 cells. Twenty-eight were down regulated in the 3dNH4 cells as shown by the heat map analysis (Additional File 8: SNP\_call\_list.xls). These results suggest a relative quiescence of transposase ORFs during healthy growth, and a burst of transcription when cells are stressed. Mutagenesis of genes involved in general metabolic pathways in *Escherichia coli* has been shown to promote earlier transposition of an IS5 family insertion sequence [29]. Media supplements to the mutated cells were shown to delay transposition events, thereby showing general starvation responses were likely involved in increased IS element activity [29].

The expression of *nif* cluster genes in the 5dNH4 sample suggests that the ammonium content of the medium was depleted, or nutrient deprived microsites had developed among the mycelia. One of the highly

expressed non-ribosomal ORFs is the pyrophosphohydrolase gene *hisE* (Francci3\_4317), suggesting that the amino acid histidine is in short supply. Additionally, a serine O-acetyltransferase was highly expressed in 5dNH4 cells, indicating activity in the cysteine synthesis pathway. Higher expression of both *ppx/gppA* ORFs (Locus tags: Francci3\_0472 and Francci3\_3920) in the 5dNH4 sample suggests that the stringent response [30] is active in response to amino acid deprivation. Two ORFs annotated as (p)ppGpp synthetases (Locus tags: Francci3\_1376 and Francci3\_1377) were actually more highly expressed in 3dN2 and 3dNH4 cells than in 5dNH4 cells.

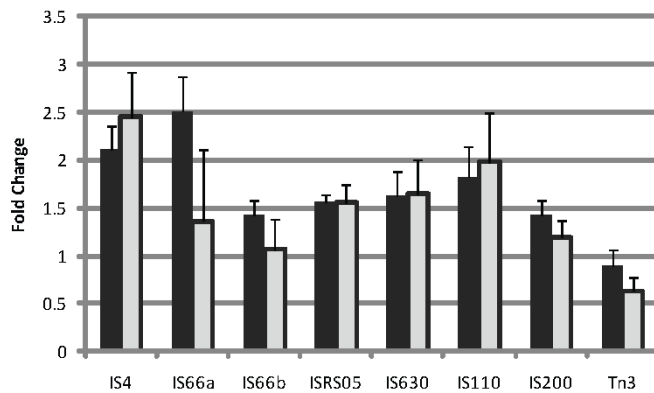
Transcription of IS elements does not directly correlate to translation [31]. Many IS elements prevent their own transposition by requiring a -1 frame shift mutation in the transcript in order to express a functional transposase protein [32]. Since the specific methods of translational control used by *Frankia* IS elements are unknown, transcriptome data alone cannot be used as a proportional metric for transposition activity. On the other hand, recent proteomic studies on the CcI3 genome have confirmed that translation of many IS elements does occur *in vivo* and in symbiosis [16,33].

#### RT-qPCR confirmation of transposase transcription

Duplicated copies of highly similar transposase ORFs presented a problem in the analysis of transcript sequence data. To compare transcription frequencies of duplicated ORFs in different culture conditions, we used RT-qPCR to amplify conserved regions of eight duplicated transposase ORF families using primers designed to amplify conserved regions in each group. The duplicates had greater than 98% nucleotide similarity with each other. The glutamine synthetase I (*glnA*) gene was used to normalize expression data as previously described [34]. We included a five-day old nitrogen fixing (5dN2) condition in our assay to better estimate transposase ORF expression in two older culture conditions (5dN2 and 5dNH4).

The results of the RT-qPCR assay confirmed the transcriptome sequence data (Figure 3). Comparing the five-day samples with three-day samples revealed an increase in transposase ORF transcription in older cultures in nearly all cases (Figure 3a). The only exception was in the case of the Tn3 family of transposases where transcription was predicted to be higher (fold change values less than one) at three days in both conditions. This may be due to transposition immunity described for other members of the Tn3 family [35]. Cross comparisons of NH4 and N2 samples revealed that nitrogen fixing cultures had more transposase transcripts from these duplicated families than from the ammonium cultures at both time points (Figures 3b and 3c). The most

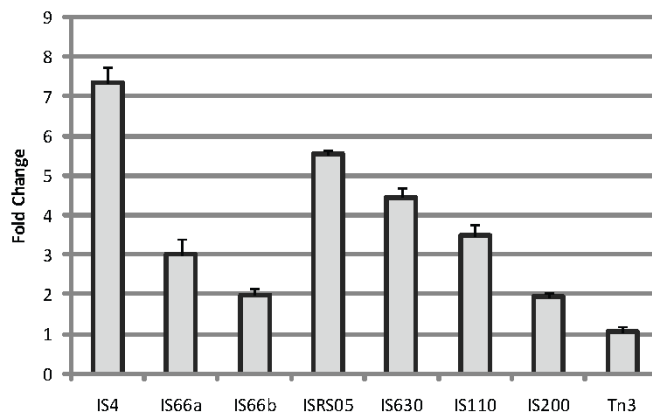
### A. 5 day sample fold change



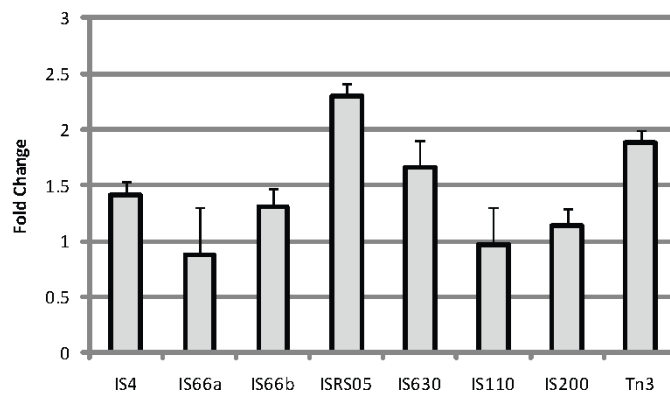
#### Fig. 5a Legend

- 5dN2 vs 3dN2
- 5dNH4 vs 3dNH4

### B. 5dN2 vs. 3dNH4 fold change



### C. 3dN2 vs. 5dNH4 fold change



Duplicated Group	Copy Number	Locus Tag
IS4	14	franccl3_2481
IS66a	6	franccl3_1864
IS66b	6	franccl3_0505
ISRS05	3	franccl3_1967
IS630	2	franccl3_1872
IS110	4	franccl3_3436
IS200	3	franccl3_3265
Tn3	2	franccl3_2347

**Figure 3 Results of the RT-qPCR assay of highly duplicated transposase ORFs.** All values indicate relative fold increase of transcription between samples standardized against *glnA* transcript levels. Panel A - fold changes of transcripts between five day and three day time points of cultures grown on N2 (black bars) or NH4 (gray bars). Panel B: fold changes of 5dN2 vs 3dNH4. Panel C: fold changes of 3dN2 vs 5dNH4 transposase ORFs respectively. The table (inset) indicates the copy number of duplicated transposase ORFs within each IS group as well as the locus tag of one of the representative members of that group. Error bars indicate standard error of triplicate reactions over each histogram.

dramatic change in transcript quantity was found for the IS4 transposases' transcripts in the 5dN2 sample that were 7.4 fold higher than levels in the 3dNH4 sample. As the representative transposase ORFs chosen for the RT-qPCR analysis were families of duplicates, a direct comparison of RT-qPCR fold change to transcriptome RPKM values was difficult to make. Still, the results of this experiment confirm the general trend of transposase ORF transcription in *Frankia* sp. CcI3: older and nitrogen-deprived cultures had higher transcription of transposase ORFs.

### Prophage and CRISPRs

ORFs with phage-related annotations were all more highly transcribed in the five-day sample with respect to both three-day samples (Table 4). Several ORFs annotated as phage integrases were expressed more than two-fold in the 5dNH4 sample when compared to the 3dNH4 sample. Comparisons of fold change among all three samples yielded many statistically insignificant differences as determined by a Kal's z-test suggesting that

these ORFs are likely transcribed at similar rates regardless of culture conditions. A phage SPO1 DNA polymerase-related protein (Francci3\_0075) was constitutively expressed in all three samples, and four phage resistance ORFs were up-regulated in the 5dNH4 sample. The latter include members of the *pspA* and *pgl* (Phi C31) families of phage resistance genes. Similar RPKM values between the two *pgl* ORFs in all three samples suggest that these ORFs are transcribed as an operon in CcI3.

CcI3 has four putative CRISPR arrays, two of which are located near clusters of CAS ORFs (data obtained from CRISPRFinder [36]). Three of the CRISPR arrays had high numbers of repeat copies (38, 15 and 20 spacers per array ordered with respect to the OriC) making alignment of ambiguous sequence reads difficult. Even the shorter 36 bp read lengths of the 5dNH4 sample could not be reliably mapped across the arrays using the CLC Genome Workshop alignment programs. As a result, few reads mapped to the array region of the CRISPR islands and numerous deletions were predicted (Additional Files 2 through 7). The CAS ORF

**Table 4 Fold changes of phage related ORFs<sup>1</sup>**

Feature ID	Annotation	5dNH4 vs 3dNH4	3dN2 vs 3dNH4	3dN2 vs 5dNH4
Francci3_0075	phage SPO1 DNA polymerase-related protein	-1.02*	1.19*	1.21*
Francci3_0114	phage integrase	-1.10*	1.54	1.70
Francci3_0407	phage integrase	1.48	1.23	-1.20
Francci3_0878	phage integrase	1.05*	1.55	1.48
Francci3_1095	phage integrase	1.46	1.62	1.11
Francci3_1144	phage integrase	2.72	1.63	-1.67
Francci3_1203	phage integrase	1.39	1.66	1.20
Francci3_1870	phage integrase-like SAM-like	3.05	1.53	-2.00
Francci3_2053	phage integrase-like SAM-like	-1.32	1.83	2.43
Francci3_2147	phage integrase	1.92	1.52	-1.26
Francci3_2228	phage shock protein A, PspA	2.47	1.43	-1.73
Francci3_2304	phage integrase	1.60	-1.24*	-1.99
Francci3_2344	phage integrase	1.59	1.20*	-1.32
Francci3_2443	putative phage-related terminase large subunit	1.34	1.84	1.37
Francci3_2954	bacteriophage (phiC31) resistance gene PglY	1.57	1.38	-1.14*
Francci3_2955	bacteriophage (phiC31) resistance gene PglZ	1.47	1.22*	-1.21*
Francci3_3052	phage integrase	1.07*	1.43	1.34
Francci3_3350	phage integrase	1.42	1.74	1.22
Francci3_3388	phage integrase	1.55	1.84	1.19
Francci3_3390	phage integrase	1.89	-1.09*	1.73
Francci3_3532	phage integrase	2.02	1.48	-1.36
Francci3_3535	phage shock protein A, PspA	-1.98	-1.86	1.06*
Francci3_3583	phage integrase	-1.34	1.39	1.86
Francci3_3734	phage integrase-like SAM-like	1.34	1.62	1.21
Francci3_4274	phage integrase	4.52	1.60	-2.83
Francci3_4338	phage integrase	-1.36	1.69	2.30

<sup>1</sup>Fold changes calculated as quotients of RPKM values

\*Insignificant p value as determined by Kal's ztest.

Negative values indicate a fold reduction of expression in the reference (later) condition.

transcripts, by contrast, were detected in all three samples. Again, transcription was modestly higher in the 5dNH4 sample than in the 3dNH4 sample (Table 5). In this instance, the 3dN2 sample had nearly two fold higher expression of all CAS ORFs when compared with the 3dNH4 sample. Comparison of the 5dNH4 and 3dN2 samples revealed insignificant fold changes as determined by a Kal's ztest.

#### SNP detection

Given the base pair resolution of RNA sequencing, it is possible to identify single nucleotide polymorphisms (SNPs). Recent analysis of the bovine milk transcriptome revealed high fidelity of SNP calls derived from an RNA-seq experiment, though the authors caution that stringent criteria are necessary to reduce false positive calls [37]. Using similar filtering criteria, we identified 215 SNPs in the 5dNH4 sample, 365 SNPs in the 3dN2 sample and 350 SNPs in the 3dNH4 sample. Comparison of the SNP populations revealed that the 5dNH4 sample had substantially different SNP calls than the 3dN2 and 3dNH4 samples. Only 21 of the putative SNPs were found in all three samples (Table 6). Twelve of these common SNPs resulted in non-synonymous amino acid changes.

There are several possibilities that may explain the variance of SNP content between the 5dNH4 sample and the two three day samples. The age of the culture is a possible, yet unlikely, contributor to a significantly different SNP pattern. *Frankia* strains are maintained by bulk transfer of cells since derivation from single colonies is problematical due to the hyphal habit of growth. Thus, over time, SNPs likely arise spontaneously. Another possibility is that errors are incorporated into the mRNA-seq libraries resulting in false positive SNPs. The Superscript III<sup>®</sup> reverse transcriptase used in the first strand cDNA synthesis was derived from a MML virus [38] and has an error rate of approximately  $3.0 \times$

$10^{-5}$  errors per base [39]. Therefore, only SNPs detected in all three samples with high coverage and multiple variant copies were likely true positive SNPs.

#### Conclusions

We deep-sequenced dscDNA libraries derived from three culture conditions of *Frankia* sp. CcI3. Overall gene expression varied more as a function of culture age than as a function of nitrogen deprivation, likely because the cell population has fewer actively growing cells at the fifth day of culture and those remaining are adapting to nutrient deprivation. In two limited nutrient environments, transposase ORFs were relatively more highly expressed than in younger ammonium grown cells. A RT-qPCR assay designed to quantify highly duplicated transposase ORFs supported the data from the mRNA-seq experiment. These results, in tandem with discovery of putative SNPs, suggests that the IS element laden CcI3 genome is in constant flux within the relatively mundane conditions of a culture flask.

#### Methods

##### Culture media and conditions

Frozen stocks of *Frankia* sp. strain CcI3, were suspended in duplicate in 200 ml of *Frankia* Defined Minimal media (FDM) containing 45 mM sodium pyruvate and 9.3 mM ammonium chloride in 500 ml flasks [40]. Cells were grown at 30°C for three or five days on FDM with or without (N<sub>2</sub> fixing cells) ammonium. Nitrogen fixing cultures were prepared using a modified iron stock as previously described [24]. Given the difficulty in quantifying viable *Frankia* cells in culture, a total of three ml of gravity-settled cells were harvested per culture flask for RNA extraction.

##### RNA extraction

*Frankia* cells were processed using a ZR Fungal/Bacterial RNA MiniPrep™ kit from Zymo Research<sup>®</sup> (<http://>

**Table 5 Fold changes of CRISPR associated ORFs<sup>1</sup>**

Feature ID	Annotation	5dNH4 vs 3dNH4	3dN2 vs 3dNH4	3dN2 vs 5dNH4
Francci3_0017	CRISPR-associated helicase Cas3, core	1.31	1.39	1.06*
Francci3_0020	CRISPR-associated protein, CT1975	2.99	1.63	-1.84
Francci3_0021	CRISPR-associated protein, CT1976	2.79	1.42	-1.96
Francci3_0023	CRISPR-associated protein Cas1	1.31	1.57	1.20
Francci3_0024	CRISPR-associated protein, Cas2	1.16	1.31	1.13*
Francci3_3341	CRISPR-associated helicase Cas3, core	1.29	1.35	1.05*
Francci3_3344	CRISPR-associated protein TM1801	1.04*	1.45	1.39
Francci3_3345	CRISPR-associated protein Cas4	1.97	1.36	-1.44
Francci3_3346	CRISPR-associated protein Cas1	1.14	1.29	1.13

<sup>1</sup>Fold changes calculated as quotients of RPKM values

\*Insignificant p value as determined by Kal's ztest.

Negative values indicate a fold reduction of expression in the reference (later) condition.

**Table 6 Detected SNPs present in all three samples**

Locus tag	Annotation	Position	Reference <sup>1</sup>	Variants <sup>2</sup>	Amino Acid Change
Francci3_0398	putative DNA-binding protein	452	G	G/A	Arg -> Gln
Francci3_1612	NLP/P60	356	G	G/A	Arg -> Gln
		375	A	A/C	Gln -> His
Francci3_1959	Transposase, IS110	1109	G	G/A	Gly -> Asp
Francci3_2025	Transposase, IS4	81	G	A/G	-
		91	C	C/T	Arg -> Cys
		119	T	T/C	Val -> Ala
Francci3_2063	hypothetical	310	A	A/C	Met -> Leu
		313	C	C/T	Pro -> Ser
		333	C	C/T	-
		353	A	A/G	Glu -> Gly
Francci3_3047	Radical SAM	93	G	G/C	-
Francci3_3251	putative signal transduction histidine kinase	293	T	C/T	Val -> Ala
Francci3_3418	SsgA	165	C	T/C	-
Francci3_4082	dnaE	3579	T	C/T	-
		3601	G	G/A	Glu -> Lys
Francci3_4107	Integrase	135	C	C/T	-
Francci3_4124	Recombinase	162	T	T/A	-
		168	C	T/C	-
Francci3_4157	Hypothetical	36	C	C/T	-
		49	A	A/G	Ser -> Gly

<sup>1</sup> The nucleotide present in the reference genome sequence of *Frankia* sp. Ccl3.

<sup>2</sup> The predicted allelic variants for the reference position nucleotide. The most common polymorphic nucleotide is listed first in the proportion.

www.zymoresearch.com) using the manufacturer's recommendations. To completely remove genomic DNA (gDNA) contamination from the RNA extraction, we performed the in-column DNase I optional step using Amplification grade DNase I (Invitrogen™, <http://www.invitrogen.com>). DNaseI incubation times were extended to 30 minutes at 37°C in order to completely remove gDNA from the sample. A final elution volume of 15 µl of RNase free water was used instead of the recommended 6 µl elution volume. Only RNA samples with a 260/280 nm wavelength ratio above 2.00 were used for library construction and RT-qPCR assays.

In order to enrich mRNA content for generating a cDNA library, we used the MICROBExpress™ Bacterial mRNA Enrichment Kit (Ambion Inc., <http://www.ambion.com>). The manufacturer's website specifies that the oligonucleotide sequence used by the kit should anneal to the 16S and 23S rRNA sequences of many eubacterial species including *Frankia* sp. Approximately 10 µg of *Frankia* total RNA in each condition was processed using the kit per the manufacturer's instructions. This procedure yielded 2 - 3.75 µg of RNA after depletion for each sample. Subsequent gel analysis and sequencing data revealed substantial 16S and 23S rRNA within the sample, suggesting only partial depletion of rRNA transcripts. Samples were nonetheless prepared

using the depletion kit in order to minimize variability due to differential handling in the experiment.

#### Complementary DNA library generation

One microgram of processed *Frankia* RNA was used in an Illumina mRNA-seq kit. The poly-dT pulldown of polyadenylated transcripts was omitted, and the protocol was followed beginning with the mRNA fragmentation step. A SuperscriptIII® reverse transcriptase was used instead of the recommended SuperscriptII® reverse transcriptase (Invitrogen™). This substitution was made in light of the higher G+C% of *Frankia* sp. transcripts (71% mol G+C) and the ability of the SuperscriptIII® transcriptase to function at temperatures greater than 45°C. Because of this substitution, the first strand cDNA synthesis stage of the protocol could be conducted at 50°C instead of 42°C. Since a second-strand cDNA synthesis was performed, the cDNA library was agnostic with respect to the strandedness of the initial mRNA. The final library volumes were 30 µl at concentrations of 40 - 80 ng/µl as determined by Nanodrop spectrophotometer.

#### Library clustering and Illumina platform sequencing

Prior to cluster generation, cDNA libraries were analyzed using an Agilent® 2100 Bioanalyzer (<http://www>.

chem.agilent.com) to determine final fragment size and sample concentration. The peak fragment size was determined to be approximately 200 +/- 25 bp in length for each sample. Twenty nmoles of each cDNA library were prepared using a cluster generation kit provided by Illumina Inc. The single-read cluster generation protocol was followed. Final cluster concentrations were estimated at 100,000 clusters per tile for the five day sample and 250,000 clusters per tile for the two three day samples on each respective lane of the sequencing flow-cell.

An Illumina® Genome Analyzer IIx™ was used in tandem with reagents from the SBS Sequencing kit v. 3 in order to sequence the cDNA clusters. A single end, 35 bp internal primer sequencing run was performed as per instructions provided by Illumina®. Raw sequence data was internally processed into FASTQ format files which were then assembled against the *Frankia* sp. CcI3 genome [Genbank: CP000249] using the CLC Genomics Workbench™ software package distributed by CLC Bio®.

*Frankia* sp. CcI3 has a several gene duplicates. This made the alignment of the short reads corresponding to the gene duplicates difficult. Reads could only be mapped to highly duplicated ORFs by setting alignment conditions to allow for 10 ambiguous map sites for each read. In the case of a best hit “tie,” an ambiguous read was mapped to a duplicated location at random. Without this setting, more than 20 ORFs would not have been detected by the alignment program simply due to nucleotide sequence similarity.

To standardize gene expression calculations among different samples, the CLC Genomic Workbench software calculates an expression value termed “reads per kilobase million” (RPKM). This calculation incorporates variable gene length in the gene expression ratio, and the total number of reads obtained from a sequencing run [41]. The equation used to determine RPKM values is as follows:

$$\text{RPKM} = \text{Number of Reads} / (\text{Kilobase length of gene} * \text{Millions of reads in dataset})$$

The RPKM value allows comparisons between datasets containing variable numbers of reads as well as expression of genes with varying lengths. Because of the disparate quantities of rRNA reads among the three samples, we removed all non-coding RNA (ncRNA) reads from the data set before calculating RPKM values. This ensures that the reads from the 5dNH4 sample, which had the lowest number of ncRNA reads, were not over-represented. Comparisons of gene expression were tested using Kal's Z-test [25]. Heat maps were generated using the Cluster 3.0 command line program (<http://bonsai.ims.u-tokyo.ac.jp/~mdehoon/software/cluster/software.htm>). Datasets were normalized and median

subtracted prior to map generation. Maps were viewed using Java Treeview [42].

Potential SNPs were filtered using the following criteria: (1) reads containing putative SNPs were discarded if they had an average quality score of less than 15; (2) the polymorphic base within the read had to have a quality score above 20; (3) at least 10× coverage of the SNP position was required; (4) the SNP had to be present in 25% of the reads at that location. Raw sequence reads and calculated RPKM values for each CcI3 ORF were uploaded to the Gene Expression Omnibus database at NCBI (<http://www.ncbi.nlm.nih.gov/projects/geo>) with the accession number GSE30680.

### RT-qPCR assays

The nucleotide sequences for the target transposase ORFs in *Frankia* strain CcI3 [genbank: CP000249] were retrieved from Genbank. Primers were designed using the Primer3 webtool (<http://frodo.wi.mit.edu/primer3/>) with settings to generate primers with a melting temperature of ~60°C. Due to the limitations of extension time in quantitative polymerase chain reactions (qPCR), primers were designed to amplify less than 200 bp of sequence when possible.

Stocks of *Frankia* sp. CcI3 cells were grown in four culture conditions that included two time points and two medium types. Three of the conditions mirrored those used in the mRNA-seq experiment (3dN2, 3dNH4 and 5dNH4). A fourth condition, consisting of cells grown in nitrogen fixing medium for five days (5dN2), was also used. Cells were harvested and RNA was purified in the same manner as used in the mRNA-seq experiment. Approximately one micro-gram of RNA from each sample was used in subsequent reverse transcriptase reactions. Complementary DNA was synthesized using the SuperscriptIII® reverse transcriptase with gene specific primers (~100 nM final concentrations per reaction mix). Synthesis of the first strand was carried out at 55°C for 50 minutes with a five minute denature step at 80°C. RT reactions were diluted ten-fold with sterile water after denaturation.

All qPCR experiments were performed using the Bio-Rad™ SsoFast® Evagreen qPCR 2X master mix. Reaction volumes were reduced to 12.5 µl. A Bio-Rad™ iQ5 real-time thermocycler was used to quantify reactions. Antibody denaturing of the SsoFast polymerase was performed at 95°C for 1.5 minutes immediately prior to any cycling step. This was followed by one 98°C denaturation for 2 minutes. Temperature cycling consisted of the following: 35 cycles of 98°C for 10 seconds then 55°C for 15 seconds and finally 65°C for 15 seconds. Melt curves (to determine if there were multiple PCR amplicons) were constructed by heating final amplified

reactions from 65°C to 95°C for 10 seconds in single degree stepwise fashion. Primer efficiencies were calculated from readings derived from a standard curve of known DNA concentrations. Relative expression levels of target genes were calculated using the Pfaffl standardization as previously described [34]. The glutamine synthetase I gene (*glnA*) was used as a reference gene to standardize relative expression in the four samples.

## Additional material

**Additional file 1: Gene lists for heatmap clusters.** List of ORFs segregated as clusters from the heat map figure (Figure 1).

**Additional file 2: 3dN2 sample dataset statistics.** Tabular output of CLC Genome Workbench software for the 3dN2 sample.

**Additional file 3: 3dNH4 sample dataset statistics.** Tabular output of CLC Genome Workbench software for the 3dNH4 sample.

**Additional file 4: 5dNH4 sample dataset statistics.** Tabular output of CLC Genome Workbench software for the 5dNH4 sample.

**Additional file 5: Pairwise comparison of three day samples.** Comparison of RPKM values from the 3dNH4 and 3dN2 samples for annotated *Frankia* sp. strain Ccl3 ORFs.

**Additional file 6: Pairwise comparison of 3dN2 with 5dNH4.** Comparison of RPKM values from the 5dNH4 and 3dN2 samples for annotated *Frankia* sp. strain Ccl3 ORFs.

**Additional file 7: Pairwise comparison of the two NH4 grown cells.** Comparison of RPKM values from the 3dNH4 and 5dNH4 samples for annotated *Frankia* sp. strain Ccl3 ORFs.

**Additional file 8: SNP calling and filtering datasets.** Excel worksheets containing raw SNP calling data from all three RNA-seq experiments.

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## Authors' contributions

DMB created the RNA-seq libraries. DMB and DRB planned the experiments, analyzed the data and wrote the manuscript. Both authors have read and approved of the final manuscript

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