

## SHORT COMMUNICATION

# Ultra-high-throughput microbial community analysis on the Illumina HiSeq and MiSeq platforms

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**DNA sequencing continues to decrease in cost with the Illumina HiSeq2000 generating up to 600 Gb of paired-end 100 base reads in a ten-day run. Here we present a protocol for community amplicon sequencing on the HiSeq2000 and MiSeq Illumina platforms, and apply that protocol to sequence 24 microbial communities from host-associated and free-living environments. A critical question as more sequencing platforms become available is whether biological conclusions derived on one platform are consistent with what would be derived on a different platform. We show that the protocol developed for these instruments successfully recaptures known biological results, and additionally that biological conclusions are consistent across sequencing platforms (the HiSeq2000 versus the MiSeq) and across the sequenced regions of amplicons.**

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DNA sequencing cost continues to decline: a vast price per sequence decrease on Illumina HiSeq2000 and MiSeq platforms further supports democratization of sequencing (Tringe and Hugenholtz, 2008). Interest in amplicon sequencing on Illumina is growing (Bartram *et al.*, 2011; Caporaso *et al.*, 2011; Zhou *et al.*, 2011), largely due to lower cost per sequence than other platforms, enabling high-throughput microbial ecology at the greatest coverage yet possible. Although some technical issues exist with community sequencing, such as PCR primer biases and differential DNA extraction efficiency from different organisms in complex communities, these techniques continue to vastly expand our understanding of the microbial world.

Here we present an amplicon sequencing protocol for the HiSeq2000 and MiSeq platforms, and apply

this protocol to sequence host-associated and free-living microbial communities to verify that biological conclusions drawn from the data are consistent across platforms and sequence reads. The HiSeq and MiSeq platforms differ markedly in scale. The HiSeq2000 produces >50 Gb per day, and in the course of a 10.8 day run produces 1.6 billion 100-base paired-end reads. By contrast, the MiSeq is for single-day experiments, and generates 1.5 Gb per day from 5 million 150-base paired-end reads. Our results capture known differences between microbial communities on each platform; biological conclusions drawn are consistent across platforms and sequence reads. This protocol is therefore ready for widespread use in microbial community analysis, such as by the Earth Microbiome Project (Gilbert *et al.*, 2010), which has adopted it for amplicon sequencing. Details on the sequencing protocol are provided as Supplementary Methods.

Twenty-four samples were sequenced on three paired-end Illumina HiSeq2000 lanes, and in one paired-end MiSeq run. The samples represented soil (source: USA; *n*=8) and several host-associated environment types: human feces (source: USA;

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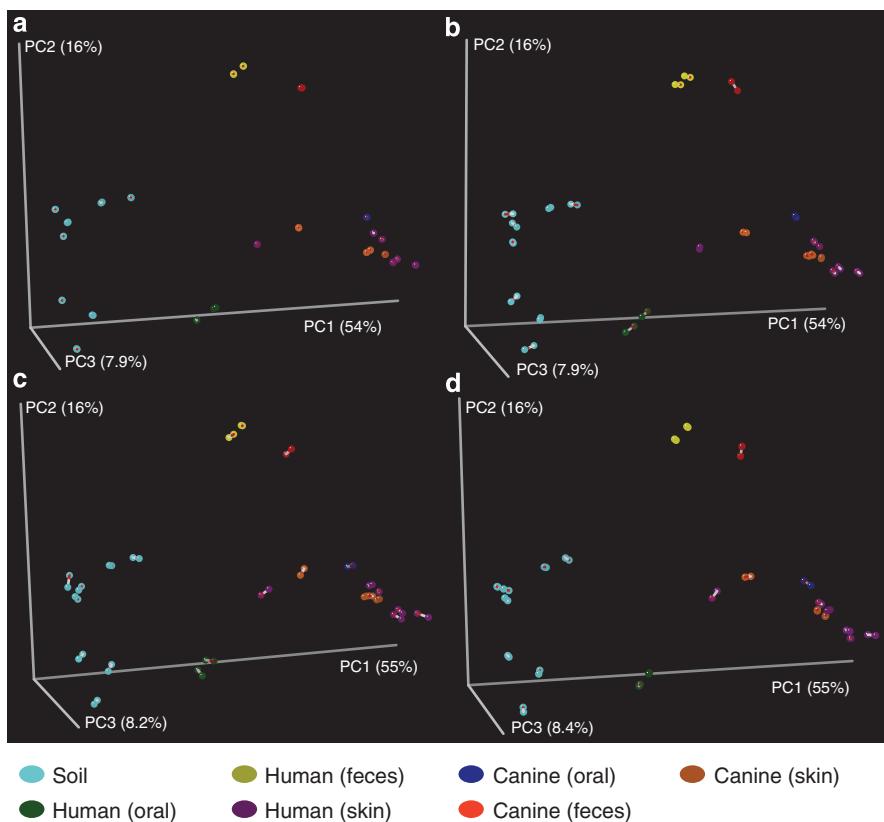
$n=2$ ), mouth (source: USA;  $n=2$ ) and skin (source: USA;  $n=6$ ); canine feces (source: USA;  $n=1$ ) mouth (source: USA;  $n=1$ ) and skin (source: USA;  $n=4$ ). These four paired-end lanes (three on HiSeq and one on MiSeq) resulted in eight sets of reads, corresponding to 5' and 3' reads from each lane. These sets of reads were treated as independent replicates to assess the reproducibility of the results.

We were primarily interested in whether known differences between microbial communities could be recaptured on these Illumina platforms to determine their suitability for large-scale surveys of microbial communities. We observed several expected results in principal coordinates plots of weighted UniFrac distances (Figure 1). First, we observed primary separation of samples based on whether they were derived from a free-living environment (soil; cyan) or host-associated environment (all other colors) (Ley *et al.*, 2008). Next we observed separation of fecal samples (yellow; red) from all other host-associated sample types (Costello *et al.*, 2009).

We were additionally interested in reproducibility across lanes and reads within and between each platform. To test this, we ran the 24 samples on three HiSeq paired-end lanes and 1 MiSeq paired-end lane, and analyzed each resulting set of reads independently. As our biological conclusions

are frequently driven by the results of principal coordinates analyses based on weighted UniFrac distances, we compared these plots using Procrustes analysis (Gower, 1975; Figure 1; Table 1) as implemented in QIIME and found that the observations were highly reproducible across lanes, read directions and platforms. All 28 possible lane/read pair combinations produced highly significant  $P$ -values based on 10 000 Monte Carlo iterations ( $P<0.0001$ ; Bonferroni-adjusted  $\alpha_{0.01}=0.0004$ ).

Taken together, these results suggest that the protocol previously developed for high-throughput community sequencing on the Illumina GAIIX has been successfully adapted for the HiSeq2000 and MiSeq platforms, again greatly decreasing the cost per sequence of amplicon sequencing to  $\sim 15\,000$  single-end reads per USD\$1 on the HiSeq2000. For example, based on our lowest high-quality sequence per lane count of 22 928 291 reads (Supplementary File 2, HiSeq 3' lane 6), if using all 2167 barcodes in each of 15 lanes on the HiSeq2000, leaving one lane for a control, then it is possible to sequence 32 505 samples in a week at a depth of 10 580 sequences per sample for approximately \$22 000 in sequencing costs. Longer barcodes could additionally be developed to facilitate more sequences per sample at a lower depth of sequencing. On the basis of the lowest high-quality sequence count on the MiSeq of



**Figure 1** Procrustes plots comparing: (a) 5' reads from HiSeq lane 6 to 5' reads from HiSeq lane 8; (b) 5' reads from HiSeq lane 6 to 3' reads from HiSeq lane 8; (c) 5' reads from HiSeq lane 6 to 5' MiSeq reads; (d) 5' MiSeq reads to 3' MiSeq reads. Lines connect paired samples.

**Table 1**  $M^2$  and Monte Carlo  $P$ -values for all Procrustes comparisons

<i>HiSeq lane 6, 5'</i>	<i>HiSeq lane 6, 3'</i>	<i>HiSeq lane 7, 5'</i>	<i>HiSeq lane 7, 3'</i>	<i>HiSeq lane 8, 5'</i>	<i>HiSeq lane 8, 3'</i>	<i>MiSeq, 5'</i>	<i>MiSeq, 3'</i>
<i>Procrustes M<sup>2</sup></i>							
HiSeq lane 6, 5'							
HiSeq lane 6, 3'	0.006						
HiSeq lane 7, 5'	0.000	0.006					
HiSeq lane 7, 3'	0.005	0.000	0.006				
HiSeq lane 8, 5'	0.000	0.006	0.000	0.005			
HiSeq lane 8, 3'	0.005	0.000	0.006	0.006	0.006		
MiSeq, 5'	0.006	0.009	0.006	0.008	0.007	0.008	
MiSeq, 3'	0.007	0.007	0.007	0.007	0.007	0.008	0.002
P-value (based on 10 000 Monte Carlo iterations)							
HiSeq lane 6, 5'							
HiSeq lane 6, 3'	0.0000						
HiSeq lane 7, 5'	0.0000	0.0000					
HiSeq lane 7, 3'	0.0000	0.0000	0.0000				
HiSeq lane 8, 5'	0.0000	0.0000	0.0000	0.0000			
HiSeq lane 8, 3'	0.0000	0.0000	0.0000	0.0000	0.0000		
MiSeq, 5'	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
MiSeq, 3'	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

1 603 532 reads (Supplementary File 2, MiSeq 3'), if using all 2167 barcodes, it is possible to sequence 2167 samples in a 12 h run at a depth of 740 sequence per sample for approximately \$800 in sequencing costs.

A relevant question is whether the decreased cost of sequencing should be applied to obtain deeper coverage of samples, or to increase the number of samples that are sequenced. Figure 1c compares the results of sequencing the same samples on the HiSeq 2000 at a median depth of 1207 709 sequences per sample and the MiSeq platform at a depth of 43 271 sequences per sample. The highly significant Procrustes result ( $P < 0.0001$ ) implies that we draw the same beta diversity conclusions from either sequencing run, despite a two order of magnitude increase in sequencing depth on the HiSeq2000. Similarly, when sampling to only 10 sequences per sample Procrustes results are still highly significant ( $P < 0.0001$ ; Supplementary Figure 1), although the higher  $M^2$  value indicates that the correlation is not as strong as when sampling to 100 sequences per sample. These observations, in agreement with studies that have addressed this question directly (Kuczynski *et al.*, 2010), suggest that increasing the sequencing depth is not likely to provide additional insight into questions of beta diversity, and we therefore argue that (for questions of beta diversity in particular) the decreased cost of sequencing should be applied to study microbial systems using many more samples, for example, in dense temporal or spatial analyses, rather than with many more sequences per sample. Of course, if the objective is to identify taxa that are very rare in communities, deeper sequencing will be advantageous. Additionally we note that while as few as 10 sequences per

sample may be useful for differentiating very different environment types (for example, soil and feces), as environments become more similar (for example, two soil samples of different pH) more sequences will be required to differentiate them.

As sequencing costs continue to decrease our studies of the microbial world can continue to increase in scope. The protocol presented here opens the HiSeq2000 and MiSeq Illumina platforms to community amplicon sequencing. The data generated by each is similar, but differs in scale and therefore support different applications. For large projects where time is less of an issue but cost per sequence is a major concern, the HiSeq platform allows massively parallel sequencing at the lowest cost. Here we show that comparable data can be generated on the MiSeq for smaller projects where it is important to process samples quickly, for example, in routine environmental or patient monitoring or in preliminary investigations for larger projects. We expect that this is another step toward the era of ubiquitous DNA sequencing, when sequencers become standard equipment in research and clinical laboratories. Finally, we show that technical replicates run on different sequencing platforms and from sequencing of different regions of amplicons should yield the same biological conclusions: critical information as more sequencing platforms become available.

## Conflict of interest

Several authors on this manuscript are employees of Illumina, Inc., whose technology is tested in this study.

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Supplementary Information accompanies the paper on The ISME Journal website (<http://www.nature.com/ismej>)

- 1   Supplementary Information
- 2   Supplementary File 1. PCR and sequencing primers, including 2,167 valid Golay barcoded
- 3   reverse PCR primers.
- 4   Supplementary File 2. Sequence counts for all lanes before and after quality filtering. The
- 5   MiSeq run included sequencing of a PhiX control.
- 6   Supplementary Figure 1: Procrustes comparison of beta diversity conclusions at different
- 7   sampling depths (all comparisons bases on 5' reads from HiSeq lane 6).
- 8   Supplementary Methods: Details on sequencing primers and protocol, read quality control,
- 9   and bioinformatics.

Primers for paired-end 16s community sequencing on the Illumina HiSeq platform using bacteria/archaeal primer 515F/806R.

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515F (forward primer) PCR primer sequence:

Field number (space-delimited), description:

- 1, 5' Illumina adapter
- 2, Forward primer pad
- 3, Forward primer linker
- 4, Forward primer

AATGATAACGGCGACCACCGAGATCTACAC TATGGTAATT GT GTGCCAGCMCCGCGGTAA

-----  
806R (reverse primer) PCR primer sequence (each sequence contains different barcode):

2168 GoLay barcoded reverse PCR primers. Each primer is followed by a barcode identifier generated specifically for this set of primers.

Field number (space-delimited), description:

- 1, Reverse complement of 3' Illumina adapter
- 2, Golay barcode
- 3, Reverse primer pad
- 4, Reverse primer linker
- 5, Reverse primer

CAAGCAGAACGCGCATACGAGAT	TCCCTTGTCTCC	AGTCAGTCAG	CC	GGACTACHVGGGTWTCTAAT	806rcbc0
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CAAGCAGAACGCGCATACGAGAT	ATCGCACAGTAA	AGTCAGTCAG	CC	GGACTACHVGGGTWTCTAAT	806rcbc5
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CAAGCAGAACGCGCATACGAGAT	AGTCGAACGAGG	AGTCAGTCAG	CC	GGACTACHVGGGTWTCTAAT	806rcbc13
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CAAGCAGAAGACGGCATACTGAGAT AACTCGCGTAC AGTCAGTCAG CC GGACTACHVGGGTWTCTAAT 806rcbc2139  
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CAAGCAGAAGACGGCATACTGAGAT TTCCCACCCATT AGTCAGTCAG CC GGACTACHVGGGTWTCTAAT 806rcbc2166  
CAAGCAGAAGACGGCATACTGAGAT GCCGCATTGAT AGTCAGTCAG CC GGACTACHVGGGTWTCTAAT 806rcbc2167

-----  
Read 1 sequencing primer:

Field number (space-delimited), description:

- 1, Forward primer pad
- 2, Forward primer linker
- 3, Forward primer

TATGGTAATT GT GTGCCAGCMGCCGCGGTAA

-----  
Read 2 sequencing primer:

Field number (space-delimited), description:

1, Reverse primer pad  
2, Reverse primer linker  
3, Reverse primer

AGTCAGTCAG CC GGACTACHVGGGTWTCTAAT

-----  
Index sequence primer:  
-----

Field number (space-delimited), description:  
1, RC of reverse primer  
2, RC of reverse primer linker  
3, RC of reverse primer pad

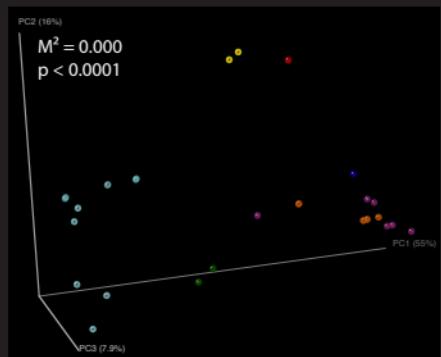
ATTAGAWACCCBDGTAGTCC GG CTGACTGACT

Generated by Greg Caporaso (gregcaporaso@gmail.com) 4/8/2011 5:00pm  
Last updated by Greg Caporaso (gregcaporaso@gmail.com) 4/21/2011 12:00pm

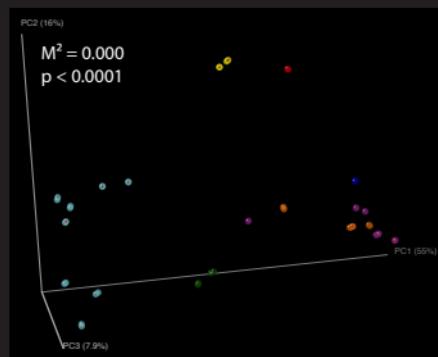
## Supplementary File 2

	Before quality filter	Before quality filter minus PhiX control	After quality filter
HiSeq 5' (lane 6)	49,757,529	49,757,529	43,227,611
HiSeq 3' (lane 6)	49,757,529	49,757,529	22,928,291
HiSeq 5' (lane 7)	41,210,187	41,210,187	36,106,618
HiSeq 3' (lane 7)	41,210,187	41,210,187	29,449,228
HiSeq 5' (lane 8)	42,098,019	42,098,019	36,833,727
HiSeq 3' (lane 8)	42,098,019	42,098,019	32,457,585
MiSeq 5'	4,920,833	2,608,041	1,685,243
MiSeq 3'	4,920,833	2,608,041	1,603,532

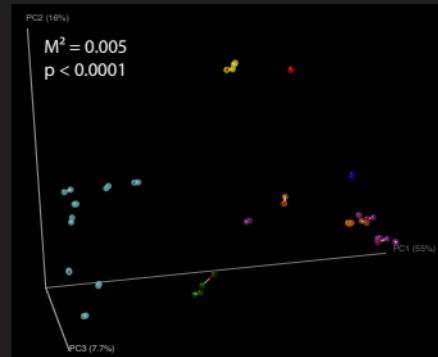
(A) 100,000 sequences/sample



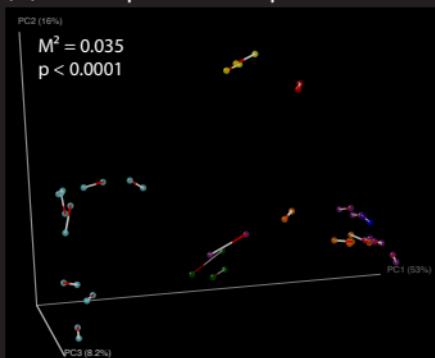
(B) 10,000 sequences/sample



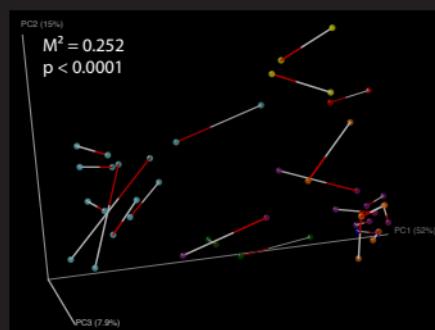
(C) 1,000 sequences/sample



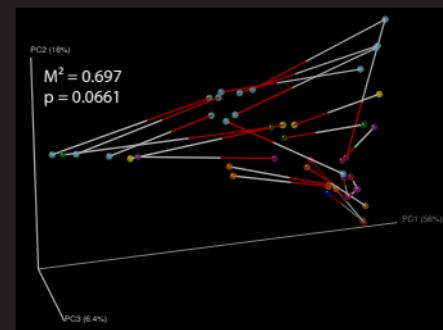
(D) 100 sequences/sample



(E) 10 sequences/sample



(F) 1 sequence/sample



- Soil
- Human (oral)
- Human (feces)

- Human (skin)
- Canine (oral)
- Canine (feces)

- Canine (skin)

1   **Ultra-high-throughput microbial community analysis on the Illumina HiSeq  
2   and MiSeq platforms**

3   **Supplementary Methods**

4   PCR and sequencing were performed using a modified version of the protocol  
5   presented in (Caporaso et al 2010b), adapted for the Illumina HiSeq2000 and MiSeq.  
6   Briefly, the V4 region of the 16S rRNA gene was amplified with region-specific  
7   primers that included the Illumina flowcell adapter sequences. The reverse  
8   amplification primer also contained a twelve base barcode sequence that supports  
9   pooling of up to 2,167 different samples in each lane. After cluster formation on a  
10   HiSeq or MiSeq instrument, the amplicons were sequenced with custom primers.  
11   These sequencing primers were designed to be complimentary to the V4  
12   amplification primers to avoid sequencing of the primers, and the barcode is read  
13   using a third sequencing primer in an additional cycle. The amplification primers  
14   were adapted from the (Caporaso, et al., 2010) protocol to include nine extra bases  
15   in the adapter region of the forward amplification primer that support paired-end  
16   sequencing on the HiSeq/MiSeq. The amplification and sequencing primers  
17   additionally contain a new pad region to avoid primer-dimer formation with the  
18   modified adapter. The primer sequences, including the 2,167 valid, secondary-  
19   structure checked Golay-barcoded reverse primers, are provided in Supplementary  
20   File 1.

21   Quality filtering of reads was applied as described previously (Caporaso et al  
22   2010b). Reads were truncated at their first low-quality base (defined by an 'A' or 'B'  
23   quality score). Reads shorter than 75 bases were then discarded, as were reads  
24   whose barcode did not match an expected barcode. Sequence counts before and  
25   after quality filtering are provided in Supplementary File 2. In addition to the  
26   twenty-four experimental samples, the MiSeq run also contained a control library  
27   made from phiX174 which, in this run, accounted for 47% of reads. The phiX  
28   control was used because of the limited sequence diversity among the 16S  
29   amplicons.

30   Reads were assigned to OTUs using a closed-reference OTU picking protocol using  
31   the QIIME toolkit (Caporaso et al 2010a), where uclust (Edgar 2010) was applied to  
32   search sequences against a subset of the Greengenes database (DeSantis et al 2006)  
33   filtered at 97% identity. Reads were assigned to OTUs based on their best hit to this  
34   database at greater than or equal to 97% sequence identity. Reads that did not  
35   match a reference sequence were discarded. Median sequence counts per sample  
36   after OTU picking were 1,319,792, 1,102,905, and 1,126,194 for the three HiSeq 5'  
37   read replicates; 718,186, 918,249, and 1,011,406 for the three HiSeq 3' read  
38   replicates; 43,966 for the MiSeq 5' reads; and 46,232 for the MiSeq 3' reads.  
39   Taxonomy was assigned to each read by accepting the Greengenes taxonomy string  
40   of the best matching Greengenes sequence. Weighted Unifrac distances were

41 computed between all samples in each replicate, and principal coordinates analysis  
42 was applied to visualize the results.

43 *HiSeq preparation and sequencing protocol*

44 16S library pools were initially analyzed by Bioanalyzer (Agilent Technologies,  
45 using DNA1000 chips) to ascertain library quality and average size distribution.  
46 The concentration of the pools was determined via Qubit (Invitrogen, using High  
47 Sensitivity reagents), and the pools diluted to 2nM. Following NaOH denaturation,  
48 the libraries were applied to a v2.5 TruSeq Paired End HiSeq flow cell/cluster kit  
49 (Illumina Inc.) at 4pM per manufacturer's instructions. For clustering, sequencing of  
50 read 1, sequencing of the index read and sequencing of read 2, customsequencing  
51 primers (IDT) were used at a final concentration of 500nMin Illumina's  
52 hybridization buffer (HT1). Sequencing on the HiSeq (v1 SBS reagents) was done  
53 according to manufacturer's instructions. Application of the library pools resulted  
54 in approximately 340k clusters/mm<sup>2</sup> and 38M reads pass-filter. Base calling was  
55 performed using CASAVA-1.7.0 (Illumina, Inc.).

56 *MiSeq preparation and sequencing protocol*

57 Quantify the library that is to be sequenced. Concentration should be recorded in  
58 Molarity. The most accurate way to quantify the sample is by conducting qPCR.  
59 Common, alternative methods include using the Agilent Bioanalyzer or the  
60 Invitrogen Qubit.

61 Use the concentration determined to dilute the sample first to 10nM, then to 2nM in  
62 a serial dilution. If the concentration of the amplicon pool is very high, it may be  
63 necessary to take the sample through a more gradual serial dilution with a final goal  
64 of 2nM.

65 Once the sample has been brought down to 2nM, the MiSeq Protocol provided by  
66 Illumina should be followed for preparation of the library for sequencing. Once the  
67 final desired concentration is reached, 15-30% denatured PhiX must be run with the  
68 amplicon pool. Add the appropriate volumes of PhiX and amplicon pool to a  
69 separate tube to maintain the appropriate concentration (Do not just spike in 25ul  
70 of PhiX into a 1000ul tube of sample). This spike helps balance the extreme base  
71 bias present in 16S amplicon samples. Up to 50% PhiX can be used to be extremely  
72 conservative when sequencing samples that require fewer reads per index, or when  
73 completing the first amplicon run to gauge the appropriate sample loading  
74 concentration.

75 Sequencing on the MiSeq requires the use of aMiSeq Reagent Cartridge. When  
76 sequencing custom 16S rRNA amplicons, the 300-cycle PE kit is used. The reagent  
77 cartridge must be thawed for about 1-1.5hrs before use. This should be thawed in a  
78 bath of room temperature ultrapure water, no higher than the water line. Once the  
79 cartridge has been thawed, place it in the 4°C refrigerator. The box containing the  
80 cartridge also contains Hybridization Buffer HT1, which should be thawed on the  
81 benchtop, then placed in the 4°C until use.

82 The MiSeq uses a “Sample Sheet” .csv file set-up through the Illumina Experiment  
83 Manager on a separate PC to dictate the parameters of each run. These instructions  
84 are based on version 1.0.31 of the Illumina Experiment Manager. When creating the  
85 sample sheet for this run, under “Select Workflow” choose “MiSeq Reporter” and  
86 then select “de novo Assembly”. (“Metagenomics” can also be selected at this stage.  
87 The important point is to select “MiSeq Reporter” as this will allow you to obtain  
88 sequences that are not demultiplexed, so demultiplexing can be performed with  
89 QIIME. This is important because QIIME can correct barcode errors while the MiSeq  
90 instrument software does not attempt to correct barcode errors.) Under the field  
91 “Select Compatible Assay” select “TruSeq DNA/RNA” (see Screenshot 1). Fill in the  
92 number listed on the cartridge you’ll be using in the “Sample Sheet Name\*” adding  
93 two zeros before the 300 (e.g. MS0002657-00300). Then, select “Paired End,” 1  
94 Index Read, Index Cycles 6, and 151x151bp (see Screenshot 2). Note that despite the  
95 barcodes being 12 bases, you should set Index Cycles to 6 in this step – this will be  
96 corrected manually in a subsequent step. On the next screen (no screenshots), fill in  
97 a Sample ID and select one of the standard barcodes Illumina provides (e.g. A001).  
98 Once the required columns have been filled-in, click in any box to see the word  
99 “valid” in green and then proceed.

100 Once this .csv file is created, it will need to be edited manually to instruct the MiSeq  
101 to conduct a 12bp index read. This is achieved by opening the appropriate sample  
102 sheet for the run in a text editor (e.g. Notepad on Windows,TextEdit on Mac, or  
103 gedit on Linux). The columns in this sheet are comma separated, so it is crucial to  
104 include/remove the appropriate amount of commas when editing the file. On the  
105 line directly under [Settings] include the command OnlyGenerateFASTQ, 1.  
106 Next, under [Data] replace the 6bp barcode with a 12bp barcode (any will do) to  
107 indicate to the instrument you want a 12bp index read. You will also need to remove  
108 the field I7\_Index\_ID, by removing both the column name and comma. In order to  
109 check that the columns appropriately align in your edited .csv, open the Sample  
110 Sheet in Excel. In Excel, you should see that the columns line-up and that the column  
111 containing I7\_Index\_ID is gone (see Screenshot 3, which is an example of what  
112 the csv should look like after you’ve edited it).

113 When preparing the sequencing cartridge, pierce the foil with a 1000ul pipette tip  
114 and add 600ul of the denatured library plus PhiX in the “Load Sample” well. Next,  
115 pierce the foil seals with a pipette tip and add 3.4ul of Index Sequencing Primer  
116 (100uM) to reservoir 13, 3.4ul of Read 1 Sequencing Primer (100uM) into reservoir  
117 12, and 3.4ul of Read 2 Sequencing Primer (100um) to reservoir 14. Next, mix the  
118 contents of each of the reservoirs (12, 13, and 14) with a Pasteur pipette to ensure  
119 that the primers added by the user are mixed with the standard Illumina cocktail  
120 already in the reservoirs. Note that you should mix the contents of each reservoir  
121 with itself so each internal mixture is homogenous - do not mix the contents of  
122 different reservoirs with one another.

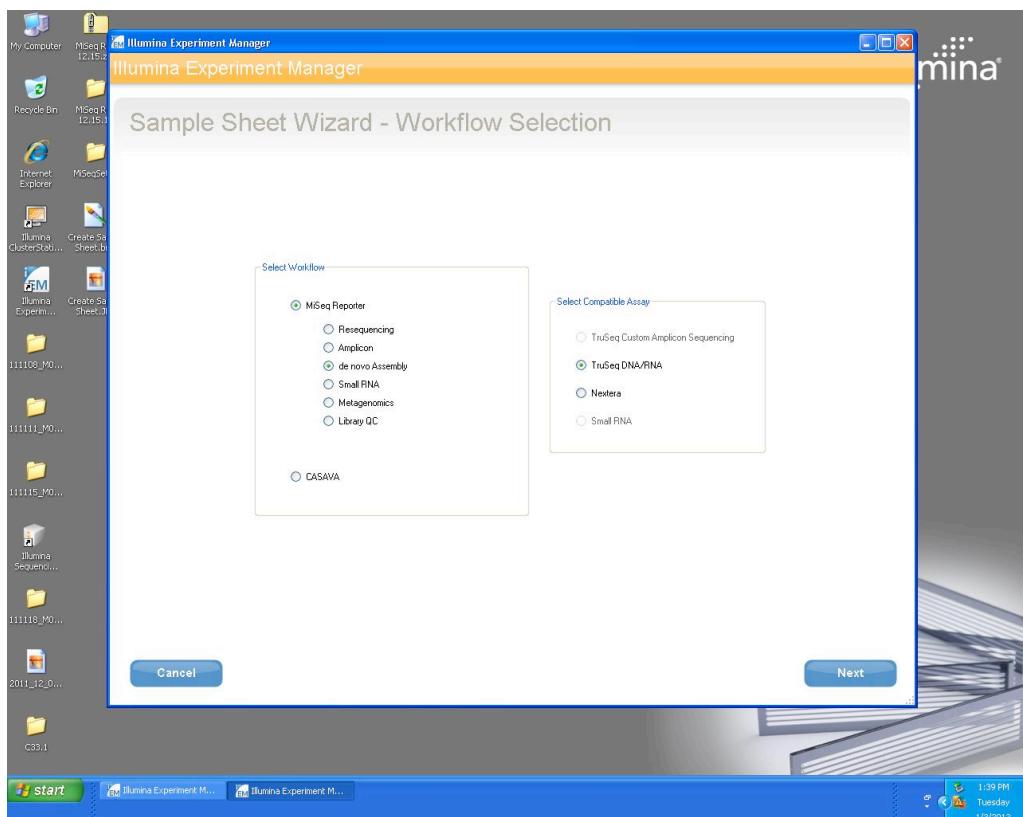
123 After loading the flow cell, buffer, and MiSeq cartridge, the machine will search for  
124 the sample sheet based on the barcode on the cartridge. If edited properly, the

125 MiSeq will have no trouble accessing your Sample Sheet, and will indicate that the  
 126 run is 314 cycles (151bp x 12bp x 151bp). The machine will throw an error that this  
 127 run requires more cycles than the 300 cycle kit can complete, and that there could  
 128 be sequence quality issues. Ignore the error and continue with the sequencing run.  
 129 There are enough reagents in the cartridge for 323 cycles.

130 As of this writing the current version of the MiSeq Control Software (MCS) is RTA  
 131 1.13.0. RTA1.14 is currently in development, and will provide better handling of  
 132 high-density data. If you're interested in using RTA1.14 before it is released you  
 133 should contact Illumina for a software patch and instructions for installing it.

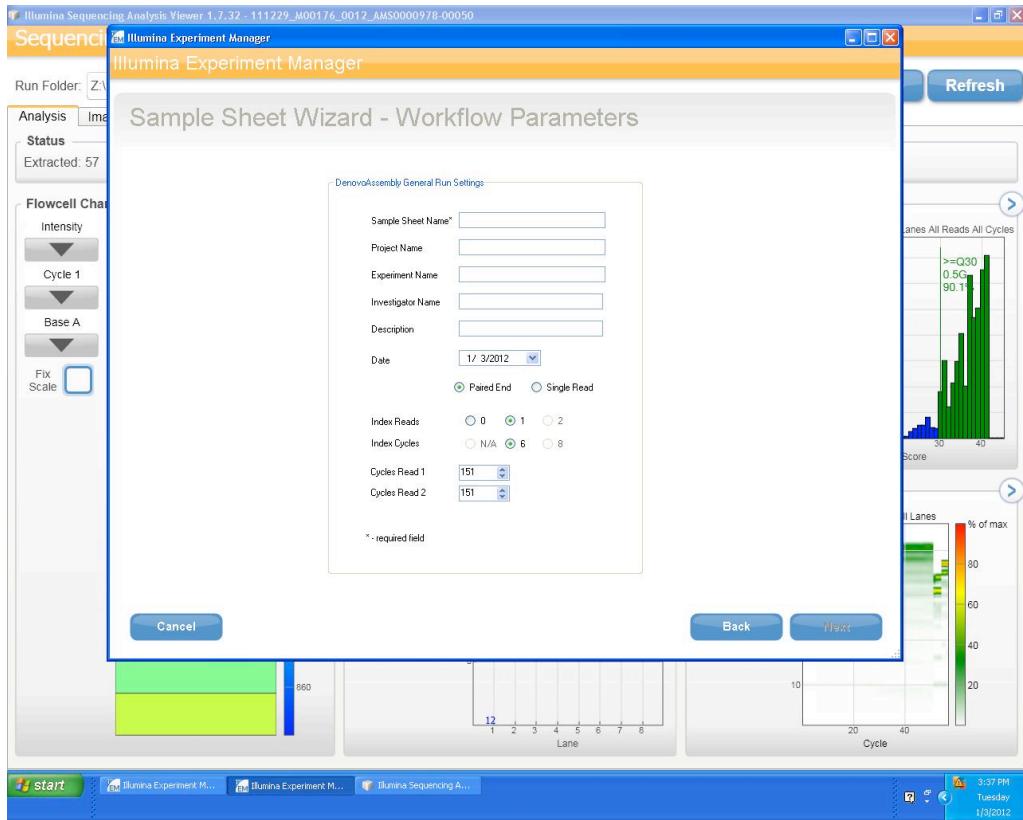
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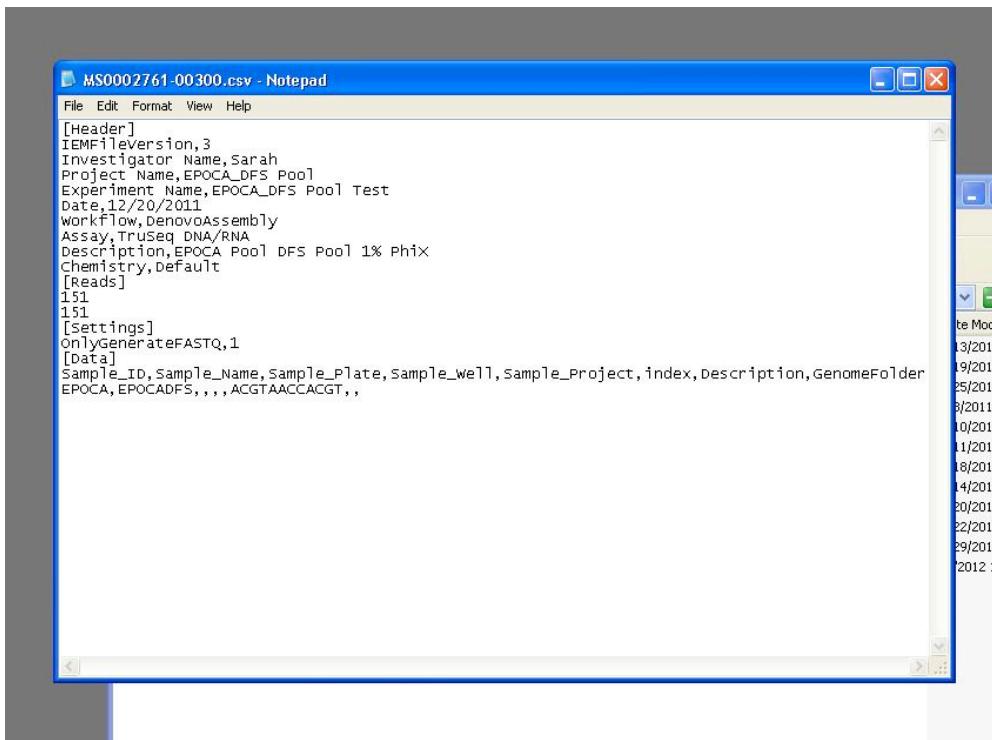
137 **Screenshot 1: Worflow selection.**



138

139 Screenshot 2: Worflow parameters.

140



141

142 Screenshot 3: Example csv file after editing.

143

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