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RESOURCE ARTICLE

vAMPirus: A versatile amplicon processing and analysis program for studying viruses

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Abstract

Amplicon sequencing is an effective and increasingly applied method for studying viral communities in the environment. Here, we present vAMPirus, a user-friendly, comprehensive, and versatile DNA and RNA virus amplicon sequence analysis program, designed to support investigators in exploring virus amplicon sequencing data and running informed, reproducible analyses. vAMPirus intakes raw virus amplicon libraries and, by default, performs nucleotide- and amino acid-based analyses to produce results such as sequence abundance information, taxonomic classifications, phylogenies and community diversity metrics. The vAMPirus analytical framework leverages 16 different opensource tools and provides optional approaches that can increase the ratio of biological signal-to-noise and thereby reveal patterns that would have otherwise been masked. Here, we validate the vAMPirus analytical framework and illustrate its implementation as a general virus amplicon sequencing workflow by recapitulating findings from two previously published double-stranded DNA virus datasets. As a case study, we also apply the program to explore the diversity and distribution of a coral reef-associated RNA virus. vAMPirus is streamlined within Nextflow, offering straightforward scalability, standardization and communication of virus lineage-specific analyses. The vAMPirus framework is designed to be adaptable; community-driven analytical standards will continue to be incorporated as the field advances. vAMPirus supports researchers in revealing patterns of virus diversity and population dynamics in nature, while promoting study reproducibility and comparability.

KEYWORDS
amino acid, amplicon sequencing, bioinformatics, diversity, DNA, RNA, virus

1 | INTRODUCTION

From the human gut to sediments in the deep ocean, viruses are abundant, diverse and shape the systems they inhabit (Breitbart et al., 2018; Correa et al., 2021; Suttle, 2007). The advent of high-throughput sequencing (HTS) techniques like amplicon sequencing has transformed the field of virology, illuminating the currently unculturable virosphere (Labadie et al., 2020; Metcalf et al., 1995; Paez-Espino et al., 2017; Zayed et al., 2022) and helping identify the impacts of viruses on ecosystem and host function (Braga et al., 2020; Breitbart et al., 2018; Thurber et al., 2017; Uyaguari-Diaz et al., 2016). Amplicon sequencing is a targeted, polymerase chain reaction (PCR)-based HTS approach that allows deep characterization of genetic variants within populations of known viruses (Short et al., 2010). The targeted nature of amplicon sequencing reduces the economic and computational investment required for spatiotemporal investigations of virus communities at ecologically relevant scales compared to shotgun sequencing approaches (see Finke & Suttle, 2019; Frantzen & Holo, 2019; Grupstra et al., 2022; Gustavsen & Suttle, 2021; Howe-Kerr et al., 2023; Montalvo-Proaño et al., 2017). However, we acknowledge that due to the lack of a universal virus marker gene, virus amplicon sequencing can only be applied to viral groups for which primers have been developed. Nevertheless, the number of studies leveraging virus amplicon sequencing has increased rapidly over the last two decades (e.g. 16 peer-reviewed publications in 1998 compared to 127 in 2021 based on a Web of Science search of 'virus amplicon sequencing', November 2022).

The general virus amplicon sequencing workflow includes: (1) Extraction of virus nucleic acid (DNA or RNA) from fractionated or unfractionated samples, (2) PCR amplification of virus marker gene or transcript, (3) HTS of virus marker gene amplicons and (4) Bioinformatic analysis of sequencing data (Short et al., 2010; Figure 1). The effective analysis and interpretation of amplicon sequencing data relies on biologically accurate binning of marker gene sequences into taxonomically or ecologically distinct units. Recognizing viral taxa or ecotypes, however, can be challenging. For example, non-model viruses have limited baseline information available to inform the selection of clustering thresholds. Other viruses, such as RNA viruses, have error-prone polymerases and produce quasispecies, a population structure consisting of large numbers of variant genomes (Domingo & Perales, 2019) that may not be easily resolved by the same clustering percentage. Alternatively, denoising algorithms which facilitate the generation of amplicon sequence variants (ASVs), offer an effective non-clustering-based processing approach to accurately identify single virus gene sequence variants within complex data. This method achieves high precision and biological accuracy by identifying

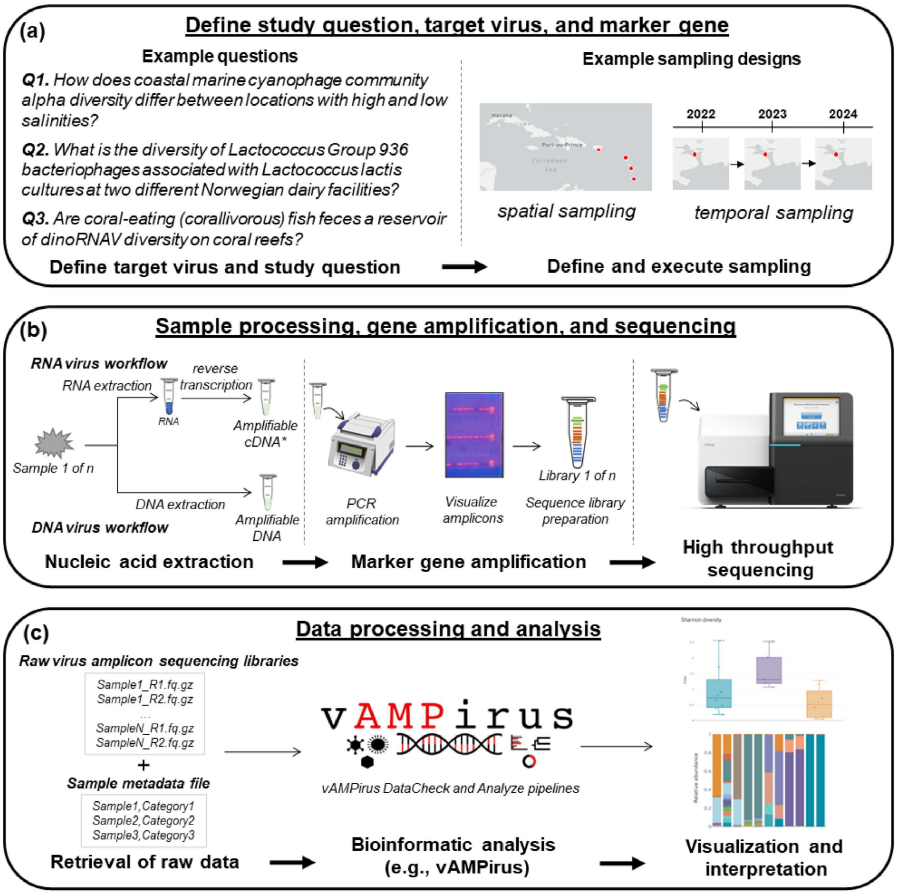

FIGURE 1 General workflow of virus amplicon sequencing projects (bolded text). *cDNA, complementary DNA.

and removing error-derived sequences during ASV generation (Callahan et al., 2017; Edgar, 2016b). In addition, since the identity of an ASV is not specific to a given dataset (as identity can be in clustering of marker gene sequences into de novo OTUs based on a percent identity value, Callahan et al., 2017), ASVs and their unique translations ('aminotypes', see Grupstra et al., 2022) can be compared directly among studies (Callahan et al., 2017).

To promote the standardization, reproducibility and cross-comparison of DNA and RNA virus amplicon sequence analyses, we developed the automated bioinformatics tool, vAMPirus (github.com/Aveglia/vAMPirus). vAMPirus intakes raw (unprocessed) virus amplicon libraries, performs all read processing and diversity analysis steps, and produces reports detailing results (e.g. relative abundance plots, community diversity metrics) with interactive figures and tables. vAMPirus supports initial explorations of viral amplicon sequence datasets via a 'DataCheck' pipeline, which generates an HTML report with information on data quality and sequence diversity. Results from the exploratory DataCheck pipeline can then be used to optimize parameters in the read processing or ASV generation steps within the vAMPirus 'Analyze' pipeline; this can improve the signal-to-noise ratio in downstream analyses. vAMPirus is integrated with the Nextflow workflow manager, which uses a configuration file that can be shared among investigators, facilitating the standardization and dissemination of virus amplicon sequence analyses across projects and research groups. To that end, we also created the vAMPirus Analysis Repository (https://zenodo.org/communities/vampirusrepo/) to act as a central location for all published vAMPirus analyses. vAMPirus is intended to be accessible to researchers with a range of bioinformatics experience levels, and includes substantial help documentation with step-by-step instructions for running the tool (https://github.com/Aveglia/vAMPirus/blob/master/docs/). By facilitating the standardization of viral lineage-specific analyses and increasing the signal-to-noise ratio in community diversity analyses, vAMPirus will enhance the effectiveness of virus amplicon studies and lead to a more developed understanding of the global virosphere.

2 | MATERIALS AND METHODS

This section outlines the pipelines and processes therein that comprise vAMPirus v2.1.0 (Figure 2). For a more detailed explanation of vAMPirus processes and output, see the manual stored in the vAMPirus GitHub repository (github.com/Aveglia/vAMPirus/).

2.1 | vAMPirus implementation and configuration

2.1.1 | Overview of vAMPirus execution

vAMPirus is composed of three main components that are recommended to be deployed sequentially: (1) A startup script to install dependencies and databases for taxonomy processes, (2) A 'DataCheck' pipeline that provides users with detailed information on data quality and diversity to inform subsequent analysis and (3) An 'Analyze' pipeline that runs a comprehensive biology-focused analysis of the data using specified parameters and program options. vAMPirus is incorporated with Nextflow, a scientific workflow manager that allows easy configuration and deployment of the program using Conda, Docker, Singularity or cloud systems like Amazon Web Services (Di Tommaso et al., 2017). Nextflow natively communicates with scheduling managers like SLURM, PBS or Torque, making it easy to run vAMPirus on high-performance computing clusters or on a local laptop or workstation. vAMPirus analyses can be configured using the Nextflow configuration file to promote efficient utilization of computing resources and reduce run times. Real-time monitoring and remote launching of vAMPirus analyses can be done using Nextflow Tower with no alterations to the vAMPirus script.

2.1.2 | vAMPirus startup script

A startup script written in BASH is provided within the vAMPirus installation directory that will automatically install dependencies and prepare the vampirus.config file for use. Users can deploy this script to download the Nextflow workflow manager and Conda package management system if these programs are not already installed/accessible on the computer system. The script can also be directed to download one or more protein/taxonomy databases to be used in vAMPirus taxonomy processes. Available databases include: (1) The proteic version of the Reference Virus DataBase (RVDB, Bigot et al., 2020), (2) NCBI virus protein RefSeq database (Brister et al., 2015) and (3) Complete NCBI NR protein database (O'Leary et al., 2016). If directed to do so, the startup script will also download the NCBI Taxonomy Database (Schoch et al., 2020) and last common ancestor (LCA) information for sequences curated within the RVDB (Bigot et al., 2020). The script then edits the vAMPirus configuration file with the updated paths to any downloaded databases and to the vAMPirus installation directory. Lastly, text documents that include general next steps for the user and commands to test the installation are printed in the vAMPirus directory. If test analyses complete successfully, the user then updates the configuration file with project-specific parameters (e.g. project name, database for taxonomy inference, primer sequence information, number of allocated threads, working memory and scheduling manager) prior to running vAMPirus on a dataset.

2.2 | Overview of the processes performed within vAMPirus

2.2.1 | Read processing and generation of amplicon sequence variants

vAMPirus currently supports single- and paired-end raw Illumina read libraries as input. By default, read processing and

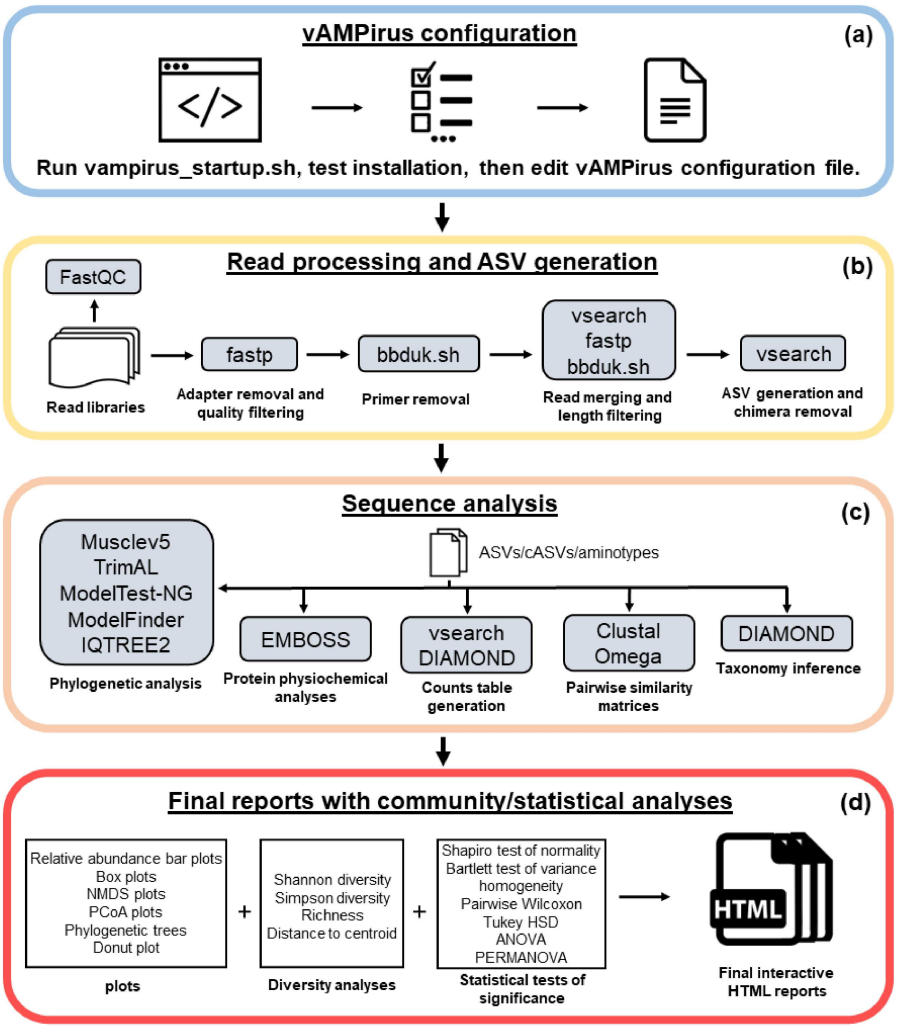

FIGURE 2 Generalized flowchart of vAMPirus v2.1.0, illustrating its configuration (box a), default analyses and programs used within the read processing (box b) and Analyze (boxes c and d) pipelines. For simplicity, only selected connections between processes are highlighted; processes generating the unique amino acid sequences ('aminotypes') and clustered ASVs ('cASVs'), as well as those specific to the DataCheck pipeline (see Figure S2) are omitted. See Figures S1–S3 for a more comprehensive illustration of vAMPirus pipelines and the processes therein. A complete description of the programs included in the vAMPirus pipelines can be found in the vAMPirus help documentation stored here: github.com/Aveglia/vAMPirus/tree/master/docs.

ASV generation processes are performed prior to entering the DataCheck or Analyze pipelines (Figure 2, yellow box; Figure S1). The read processing pipeline begins with a check of raw libraries using FastQC (v0.11.9, Andrews, 2010), which creates and stores reports for review by the user. As FastQC is running, the program fastp (v0.20.1, Chen et al., 2018) automatically detects and removes adapter contamination, and performs quality/length filtering based on user-set parameters in the configuration file. fastp also performs over-representation analysis and (for paired-end input) base error correction during this step. Next, primers are removed from adapter-less reads using the bbduk.sh program within the BBTools software package (Bushnell, 2014), and then another FastQC report is generated and stored. If data are paired-end, cleaned reads are then merged using the program VSEARCH (v2.21.1, Rognes et al., 2016). Next, all (merged or single-end) reads from all libraries are concatenated into a single fastq file. For accurate ASV generation, it is imperative that the merged reads be the same length (Edgar, 2016b). To ensure this, merged reads are globally trimmed to a user-specified maximum read length using fastp. Merged reads with the set length are then extracted from the total merged read file using the program bbduk.sh and dereplicated using the program VSEARCH (v2.21.1, Rognes et al., 2016), producing a unique read file containing read representation information. Amplicon sequence variants are then generated from this unique read file with VSEARCH and the UNOISE3 algorithm (Edgar, 2016b; Rognes et al., 2016). Chimeric ASVs are detected and removed using VSEARCH and the UCHIME3 de novo algorithm (Edgar, 2016a). Prior to entering downstream pipelines, vAMPirus provides users the option to filter ASVs with DIAMOND blastx (v2.0.15, Buchfink et al., 2015) to remove non-target sequences or to focus their analyses on a subset of ASVs/aminotypes. These steps produce a final ASV fasta file that is then used as input for the DataCheck and Analyze pipelines.

2.2.2 | Amplicon sequence variants and 'aminotypes'

By default, vAMPirus generates nucleotide-based (ASV) and amino acid-based (aminotype) results. ASVs support cross-study comparisons and offer a statistically supported view of virus sequence diversity, as biologically inaccurate sequences are removed during denoising (Callahan et al., 2017; Edgar, 2016b). However, ASV results for virus lineages with high mutation rates (e.g. RNA viruses with quasispecies heterogeneity) may still contain high levels of noise that mask biological patterns. It may be beneficial to group ASVs into distinct clusters based on genetic or ecological similarities in such use cases. In vAMPirus, 'aminotypes' (unique amino acid sequences, Grupstra et al., 2022) are generated by translating ASVs with VirtualRibosome (v2.0, Wernersson, 2006; the appropriate reading frame is determined by VirtualRibosome, see vAMPirus help documentation for additional information on sequence translation) and subsequently dereplicating these translations using the program CD-HIT with the option '-c' equal to 1.0 (v4.8.1, Fu et al., 2012; Li & Godzik, 2006). As direct products of specific ASVs, aminotypes maintain sequence tractability, reproducibility and comparability, and therefore differ from de novo OTUs or clustered ASVs (cASVs; see Section 2.2.3). The 'aminotyping' approach not only reduces noise; it also removes sequences with internal stop codons (a deleterious mutation) and reveals nonsynonymous mutations that may indicate differences in virus functionality (e.g. infection efficiency, host range; DeFilippis & Villarreal, 2000).

vAMPirus provides two additional (optional) ASV or aminotype 'grouping' approaches that are alternatives to de novo clustering: Minimum Entropy Decomposition (MED) and phylogeny-based clustering or 'phylogrouping'. MED is a method of sequence clustering that utilizes Shannon entropy (Shannon, 1948) to partition marker gene datasets into 'MED nodes' (Eren et al., 2015). With this approach, users identify sequence positions in a set of ASVs or aminotypes that are information-rich (positions of high variability) or information-poor (positions of high conservation) and use these positions to assign ASVs/aminotypes to 'MED groups' (sequences with identical bases at specified positions) (Eren et al., 2015). Users can also specify and assign sequences to MED groups based on sequence positions of interest (e.g. positions of a protein sequence known to influence a viral characteristic such as host cell attachment; see Harvey et al., 2021). Phylogrouping is performed with the TreeCluster program (v1.0.3, Balaban et al., 2019). With this approach, ASV or aminotype sequences are assigned to 'phylogroups' based on user specified TreeCluster parameters and the phylogenetic tree produced during analysis (see Figure 4E,F). All grouping methods can be applied at the same time; coupled with the use of the Nextflow '--resume' feature, adjusting specific parameters and generating new results to review and compare is straightforward and does not require re-running the entire DataCheck or Analyze pipelines.

2.2.3 | Optional de novo sequence clustering

vAMPirus provides the option to perform de novo clustering of ASVs into cASVs based on pairwise nucleotide (ncASV) and/or protein (pcASV) sequence similarity using the programs VSEARCH (Rognes et al., 2016) and CD-HIT (Fu et al., 2012; Li & Godzik, 2006), respectively. This differs from traditional de novo OTUs in that for cASVs, denoising of sequences is done prior to clustering. De novo clustering of ASVs is most useful for more developed virus systems where the degree of sequence divergence between taxonomically or ecologically distinct groups is known (e.g. poxviruses; see Deng et al., 2022). Note that, from a methodological standpoint, representative sequences generated by a cASV approach exhibit the same issues as de novo OTUs (e.g. dataset dependence; see Callahan et al., 2017).

2.2.4 | vAMPirus DataCheck pipeline and report

The vAMPirus DataCheck pipeline can help investigators determine the optimal parameters for read processing, ASV generation, and other downstream analyses conducted in the Analyze pipeline. The DataCheck pipeline is particularly beneficial for investigators working on nascent virus systems because it facilitates the informed establishment of gene-, lineage- or system-specific analysis standards. The pipeline produces an HTML report that displays information such as sequencing success per sample, read characteristics (e.g. read length, GC content) and ASV/aminotype sequence properties. The DataCheck pipeline also provides insight into the ASV sequences by clustering them across a range of nucleotide and amino acid similarities and plotting the resultant number of cASVs per similarity value. Briefly, nucleotide-based de novo cASVs are produced by clustering ASV sequences according to 24 different percent identity values (including: 55%, 65%, 75% and each whole number percentage from 80% to 100%) with VSEARCH. To generate de novo pcASVs, ASVs are first translated using the program VirtualRibosome (v2.0, Wernersson, 2006), then clustered into de novo pcASVs using the same 24 percent identities with the program CD-HIT (v.4.8.1, Fu et al., 2012; Li & Godzik, 2006). For each percent identity value, the number of ncASVs and pcASVs is quantified and visualized as a scatter plot in the DataCheck report. This is a common approach used to determine the clustering percentage (e.g. Gustavsen & Suttle, 2021): the percent similarity at which there is no longer a linear rise in the number of cASVs (the inflection point) is selected for sequence clustering. Optionally, users can also apply the program oligotyping (Eren et al., 2015) to calculate Shannon entropy values per sequence position for both ASV and aminotypes, which is then displayed in the report. An example vAMPirus DataCheck report is available at github.com/Aveglia/vAMPirusExamples.

2.2.5 | vAMPirus Analyze pipeline and report

The Analyze pipeline includes multiple analyses (e.g. phylogenetics, taxonomy inference); results are summarized in a final HTML report with tables and interactive figures (Figure S3). The pipeline also organizes and stores output (e.g. counts tables, similarity matrices, taxonomy files) from these analyses within a user-specified results directory. Integration into Nextflow allows different analytical approaches (e.g. ASV grouping approach) to be run in parallel. Primary processes and analyses are summarized below; additional processes, such as percent similarity matrix generation and protein physiochemical property analyses are reviewed in the supplemental materials (Section S1).

Counts table generation

Nucleotide- and amino acid-based counts tables are generated within the Analyze pipeline. Counts tables for ASVs and ncASVs are produced using the VSEARCH program and the USEARCH algorithm (Edgar, 2010). Optionally, users can replace the use of the USEARCH algorithm with the use of the '--search_exact' feature provided by VSEARCH for exact ASV counts tables (Rognes et al., 2016). The aminotype and pcASV counts tables are generated by aligning translated merged reads to reference amino acid sequences with DIAMOND blastx (Buchfink et al., 2015). Sequence abundance information (in a comma delimited counts table) is then generated with a custom BASH script, which quantifies the number of alignments to each reference aminotype or pcASV from the DIAMOND output file. Users have the option to edit and adjust option parameters for the VSEARCH and DIAMOND counts table generation processes within the configuration file. All count files are stored in the results directory and are processed and visualized within Analyze reports as relative abundance bar plots.

Taxonomy inference

Sequence taxonomy is inferred using DIAMOND blastx or blastp via the user-specified protein database and the option parameters specified in the vAMPirus configuration file. The default parameter values for these revisable DIAMOND options within the vAMPirus configuration file were informed by Pearson (2013). Users should be aware that modifying these parameters may impact the likelihood of false negatives or false positives in taxonomy results. Users should also be aware that virus sequence databases are frequently modified and vary in their representation of specific viral groups; thus, database selection can also potentially influence taxonomy results. The taxonomy process produces several files that are stored within a DIAMOND specific directory: (1) Unmodified DIAMOND output file, (2) fasta file of taxonomy assignments within the sequence headers and (3) Results summary files (phyloseq taxonomy file, tab-separated summary file and summary table of the abundance of specific hits). Taxonomy inference results are visualized in the Analyze report as a donut plot.

Phylogenetic analysis

Phylogenetic analyses of ASVs, cASVs and aminotypes are conducted within the Analyze pipeline and all output files are stored in a dedicated directory within the results directory. First, sequences are aligned using the program muscle (v5.1; Edgar, 2021) and then trimmed automatically using the program trimAl (v1.4.1, Capella-Gutiérrez et al., 2009) using a heuristics-based approach. By default, substitution model testing is done with Modeltest-NG (v0.1.7, Darriba et al., 2020). The program IQTREE (v2.2.0.3; Minh et al., 2020) is used to generate a maximum-likelihood tree. The substitution model used to generate the tree can be set by the user, sourced from Modeltest-NG results or automatically selected with ModelFinder (Kalyaanamoorthy et al., 2017). The tree produced is then used for phylogrouping with TreeCluster and is visualized in the Analyze report. Within the report, the user has the option to colour code nodes based on sequence identity, taxonomy hit, MED group or phylogroup assignment.

vAMPirus Analyze reports

The final process within the Analyze pipeline generates HTML reports using R Markdown (v2.3; Xie et al., 2018). By default, an individual summary report containing community composition/diversity, taxonomy and phylogeny results is generated for ASVs, aminotypes and cASVs. Users provide a metadata file that includes the sample name and category used to group the samples (i.e. sample treatment, location) for alpha and beta diversity analyses. vAMPirus summary reports are interactive and include: (1) Pre- and post-processing read statistics in tables and plots, (2) Rarefaction curves, (3) Shannon's diversity (H), Simpson's diversity (reported as $1\text{-}D$), richness and distance to centroid box plots with statistical tests (Shapiro–Wilk normality test, Bartlett test of variance homogeneity, Kruskal–Wallis rank sum test, Wilcox test, ANOVA and Tukey HSD, as appropriate), (4) Two- and three-dimensional NMDS plots (if no convergence, then PCoA plots), (5) Relative abundance bar plots, and (6) Taxonomy and phylogenetic results. An example vAMPirus Analyze summary report can be downloaded and reviewed at github.com/Aveglia/vAMPirusExamples.

2.3 | vAMPirus analysis repository

To encourage and simplify the dissemination of parameters and non-read files needed to reproduce vAMPirus analyses, we created the 'vAMPirus Analysis Repository' (zenodo.org/communities/vampirusrepo/). The vAMPirus Analysis Repository is a Zenodo Community intended as a central location where investigators can deposit vAMPirus configuration files, metadata files, databases used for taxonomy assignment or ASV filtering, and any other files required to reproduce an analysis. Instructions and recommendations for submission are available in the vAMPirus manual (shorturl.at/uCO28). Once uploaded, submissions to the vAMPirus Analysis Repository are given a DOI.

3 | VALIDATING THE vAMPirus WORKFLOW WITH PUBLISHED DOUBLE-STRANDED DNA (dsDNA) VIRUS DATASETS

We tested the ability of vAMPirus' analytical workflow to recapitulate key findings from two benchmark peer-reviewed dsDNA virus studies (detailed in Table 1). Research questions associated with each study are used as examples in Figure 1A (Finke & Suttle, 2019; Figure 1A, Q1; Frantzen & Holo, 2019; Figure 1A, Q2). For each dataset, we conducted a vAMPirus analysis that replicated the analysis from the associated published paper closely, directly integrating parameters (when available) to ensure fidelity to the original methods (see Tables S1 and S2). For example, if a study generated de novo OTUs based on 97% nucleotide identity, the vAMPirus equivalent was ncASVs generated at 97% nucleotide identity with similar data quality control constraints (e.g. same minimum sequence length, minimum quality score). This approach allowed for near-direct comparisons between the vAMPirus-generated results and those reported in the source manuscripts.

Overall, vAMPirus identified the same biological patterns as those published by Finke and Suttle (2019, Figure 3) and Frantzen and Holo (2019, Figure 4) from their respective sequence datasets, and detected additional (previously unreported) virus diversity (Table 1). For example, Finke and Suttle (2019) reported increased cyanophage community alpha diversity in samples collected from sites with higher salinity (>27.5 practical salinity units, Figure 3a,b); this pattern was present in the corresponding vAMPirus results (Figure 3c-f), which included 86% more cyanophage pcASVs relative to the number of OTUs reported in Finke and Suttle (2019; Table 1). Similarly, the patterns of lactococcal phage OTU richness and relative abundances per sample reported by Frantzen and Holo (2019; Figure 4a) were also present in the vAMPirus results (Table 2; Figure 4b). vAMPirus reported 43% more lactococcal phage ncASVs, relative to the OTUs reported by Frantzen and Holo (2019; Table 1, Figure 4). In addition, vAMPirus ASV-level analysis (Figure 4c) revealed high lactococcal phage nucleotide-level diversity ($n = 531$), yet aminotyping results (Figure 4d) suggest that the mutations underlying this richness mostly result in synonymous mutations: ASV sequences translated to only 29 aminotypes. Aminotype phylogrouping (see Section 2.2.2) of these data with TreeCluster highlighted a previously hidden overlap of lactococcal phage diversity across samples and dairy plants (Figure 4f).

Some variation between results obtained from vAMPirus and previous publications was expected, as the pipelines used in these comparisons were not identical. A key distinction between the methods employed in the source papers and vAMPirus is the incorporation of a denoising step, which identifies statistically supported and biologically significant amplicon sequence variants (ASVs) in the data (Callahan et al., 2017). Since vAMPirus uses ASVs as the foundation for all analyses (including clustering into de novo OTUs), stringent downstream filtering – like the removal of singleton OTUs to prevent sequencing-error derived sequences in the analysis – is not necessary, thereby increasing sequence retainment which can increase observed sequence diversity in end results. In fact, the only striking difference between the original results (in Finke & Suttle, 2019 and Frantzen & Holo, 2019) and those produced by vAMPirus is the higher number of pcASVs and ncASVs (respectively) identified with vAMPirus. Taxonomy results generated with vAMPirus by DIAMOND blastx aligning sequences to the NCBI virus RefSeq database verified that the produced pcASVs (from Finke & Suttle, 2019 dataset) and ncASVs (from Frantzen & Holo, 2019) are of cyanophage and lactococcal phage origin, respectively (Figures S4 and S5). The higher cASV diversity identified by vAMPirus relative to original analyses could stem from various pipeline differences, including the handling of singleton OTUs/cASVs (vAMPirus retains, rather than removes, singletons). vAMPirus analyses also leveraged the most recent NCBI-curated database for pre-analysis sequence filtering. This updated database likely includes a greater number of reference sequences (compared to boutique databases in Finke & Suttle, 2019), resulting in higher sequence retention post-filtering. Higher read merging success could have occurred in vAMPirus analyses (using VSEARCH) relative to the original studies (using PEAR or USEARCH); this may have increased the number of sequences and diversity in downstream processes. Finally, vAMPirus' de novo cASV generation, instead of reference-based clustering methods, as employed by Finke and Suttle (2019), may have resulted in the identification of higher cASV diversity. In conclusion, despite minor variations in results and pipeline characteristics, the core findings reported in the source manuscripts were strongly recapitulated by vAMPirus.

TABLE 1 Overview of test datasets used during vAMPirus development, including the methods and results from the original (published) analysis, as well as results from vAMPirus analysis. vAMPirus results were generated using de novo clustering of ASVs into 'clustered ASVs' (cASVs) based on pairwise nucleotide (ncASV) and protein (pcASV) sequence similarity.

Study	Target dsDNA virus group	Target gene	Original methods	# published OTUs	# cASVs (vAMPirus, this study)
Finke and Suttle (2019)	Myoviridae (T4-like cyanophage)	DNA polymerase	Reference-based OTU clustering at 97% protein identity	606	1,128 97% pcASVs
Frantzen and Holo (2019)	Siphoviridae (lactococcal bacteriophage)	Portal protein	OTU clustering at 99.5% nucleotide identity	151	216 99.5% ncASVs

Abbreviation: dsDNA, double-stranded DNA.

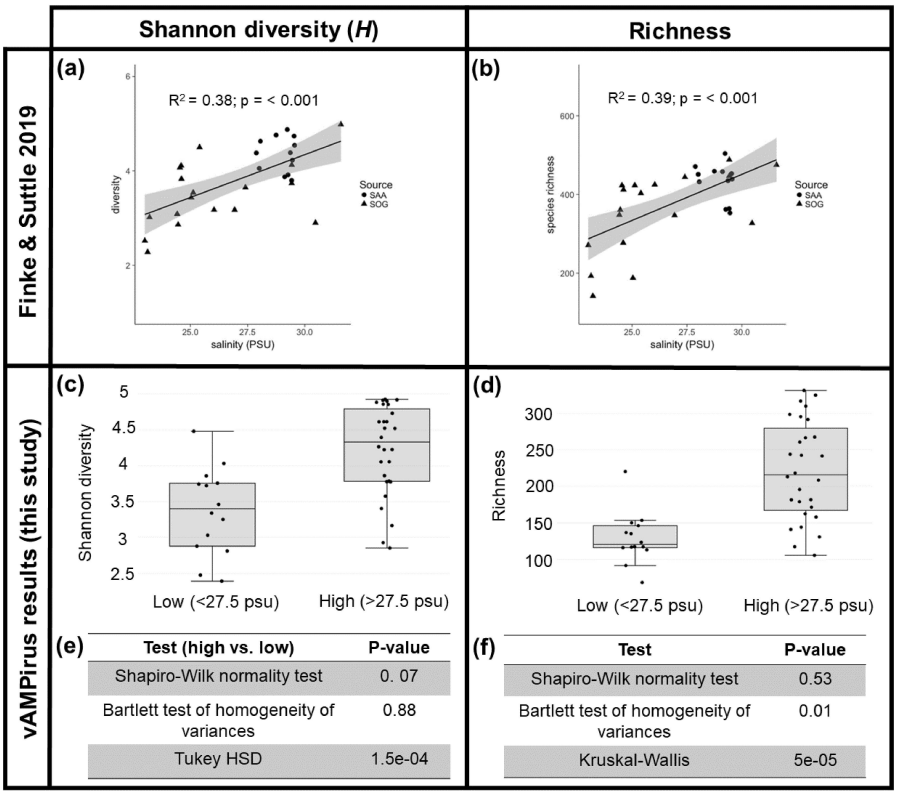

FIGURE 3 Comparison of results published by Finke and Suttle (2019) to those generated by the vAMPirus workflow for the same virus amplicon sequence dataset. The significant positive relationship between salinity and viral diversity (Shannon diversity (*H*) and richness) reported by Finke and Suttle (2019, panels a and b) was reproduced by vAMPirus (panels c-f). Panels I and II display original results from Finke and Suttle (2019), based on 97% amino acid similarity OTUs. Panels c, d, e and f include vAMPirus 97% pcASV results. Figures and statistics from Finke and Suttle (2019) and vAMPirus Analyze reports are presented with slight modifications to promote comparability. For the vAMPirus analysis, which performs comparisons among categorical sample groups set by the user, all samples were assigned to either 'high' (>27.5) or 'low' (<27.5) salinity (practical salinity units; psu) groups. Figures from Finke and Suttle (2019) reprinted with permission from authors.

4 | APPLYING vAMPirus TO STUDY A NOVEL ENVIRONMENTAL RNA VIRUS DATASET

4.1 | RNA virus study description

Dinoflagellate-infecting RNA viruses (dinoRNAVs) are positive-sense, single-stranded RNA viruses hypothesized to infect the dinoflagellate symbionts (Family Symbiodiniaceae) that live in the tissues of reef-building stony corals (Correa et al., 2013; Grupstra et al., 2022; Veglia et al., 2022). Although dinoRNAVs can be prevalent in coral colonies (Grupstra et al., 2022; Howe-Kerr et al., 2023; Montalvo-Proaño et al., 2017; Veglia et al., 2022), it is unclear how dinoRNAVs (or Symbiodiniaceae infected by dinoRNAVs) are transmitted among colonies. Recent work has shown that corallivorous (coral-eating) fishes disperse 100s of millions of live Symbiodiniaceae cells across reefscapes in their faeces each day (Grupstra et al., 2021). To assess the extent to which corallivorous fish faeces disperse dinoRNAVs in their faeces, we characterized the presence and diversity of dinoRNAVs in various environmental reservoirs using amplicon sequencing of the dinoRNAV major capsid protein (*mcp*) gene (following Grupstra et al., 2022; Howe-Kerr et al., 2023). Given that dinoRNAV communities can vary across coral species and colonies (Grupstra et al., 2022; Howe-Kerr et al., 2023; Montalvo-Proaño et al., 2017) and that corallivorous fish actively 'sample' corals while feeding (Grupstra et al., 2021), we hypothesized that corallivorous fish faeces are a reservoir of dinoRNAVs and that fish faeces-associated dinoRNAV communities exhibit higher alpha diversity than coral colony-associated dinoRNAV communities. We generated 19 dinoRNAV *mcp* amplicon sequencing libraries from coral colony biopsies (*Acropora hyacinthus*, $n = 8$; *Pocillopora* species complex, $n = 5$), as well as the faeces of corallivorous fishes (*Chaetodon reticulatus*, $n = 4$; *Chaetodon ornatissimus*, $n = 2$). All samples were collected from reefs off the north shore of Moorea, French Polynesia (South Pacific). Methods for sampling and sample processing to generate virus amplicon sequencing libraries are described in Grupstra et al. (2021), Grupstra et al. (2022), and Howe-Kerr et al. (2023). DinoRNAV *mcp* amplicon libraries were processed and analysed using vAMPirus (vAMPirus configuration files for this analysis at doi.org/10.5281/zenodo.7574173).

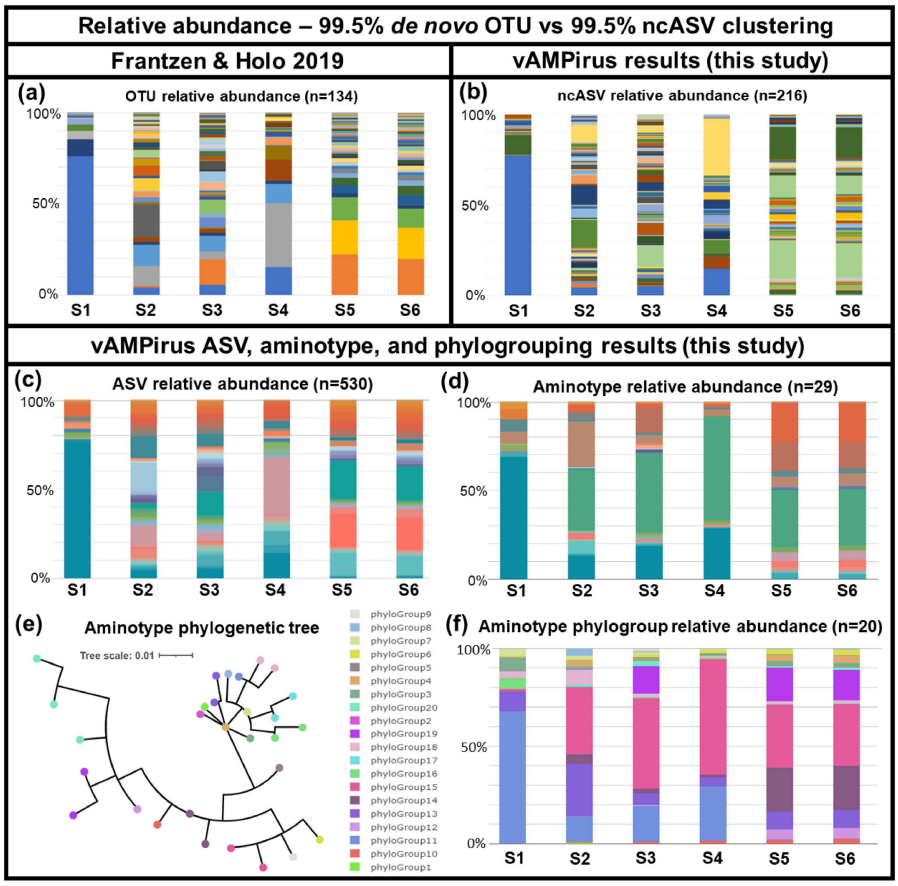

FIGURE 4 Comparison of results published by Frantzen and Holo (2019) to those generated by vAMPirus for the lactococcal phage amplicon sequence dataset. *X*-axis labels on relative abundance bar plots (S1-S6) represent dairy samples 1–6 analysed in the source paper. Patterns of lactococcal phage OTU relative abundance reported by Frantzen and Holo (2019; panel a) were recapitulated in vAMPirus ncASV results (panel b). Panel a displays original relative abundances of de novo OTUs based on 99.5% nucleotide similarity from Frantzen and Holo (2019). Panel b displays vAMPirus-generated 99.5% similarity ncASV relative abundance results. Panels c-f demonstrate additional analyses output by vAMPirus, including ASV relative abundances, aminotype relative abundances, aminotype phylogeny with nodes coloured by sequence phylogroup assignment, and aminotype phylogroup relative abundances. *X*-axis labels for all relative abundance graphs refer to dairy sample identity listed in Table 2. Colours in panels a–d are plot-specific; similar colours across these panels do *not* indicate same sequences/clusters. However, colours assigned to phylogroups are consistent across panels e and f. Figure from Frantzen and Holo (2019) reprinted with permission from authors.

TABLE 2 Comparison of Lactococcus phage sequence richness per sample between Frantzen and Holo (2019) results and vAMPirus (this study) results. Dairy samples S1-S6 (this work) correspond to dairy samples 1–6 in the source paper.

	Dairy sample	S1	S2	S3	S4	S5	S6
	Dairy plant	1	1	1	2	2	2
Frantzen and Holo (2019)	# of OTUs with >100 reads	11	46	55	26	54	59
vAMPirus results	# of ncASVs with >100 reads	25	121	117	47	66	63

4.2 | RNA virus study results and discussion

Amplicon sequencing of the dinoRNAV *mcp* gene produced a total of 7.4 million raw paired-end reads across 19 samples representing three potential reservoirs of dinoRNAV diversity across the reef. The 7.4 million raw paired-end reads were processed and reduced to 2.8 million merged reads at the expected amplicon length of 420 bases. Merged *mcp* amplicons dereplicated into 1.1 million unique sequences from which 481 ASVs and 191 aminotypes were identified. The ASV-level results did not identify a significant difference in dinoRNAV richness in corallivore faeces versus coral colonies (Kruskal–Wallis *H*-test: p-value = 0.14, Figure 5a). Aminotype results, however, revealed that dinoRNAV richness is significantly higher in corallivore faeces, relative to *Pocillopora* coral colonies (Figure 5B; Kruskal–Wallis *H*-test: p-value = 0.005; Wilcoxon signed-rank test: *Pocillopora* vs. corallivore, $p = 0.01$, *Pocillopora* vs. *Acropora*, $p = 0.04$). We interpret that a biological difference in richness likely does exist between dinoRNAV communities in corallivore faeces versus those

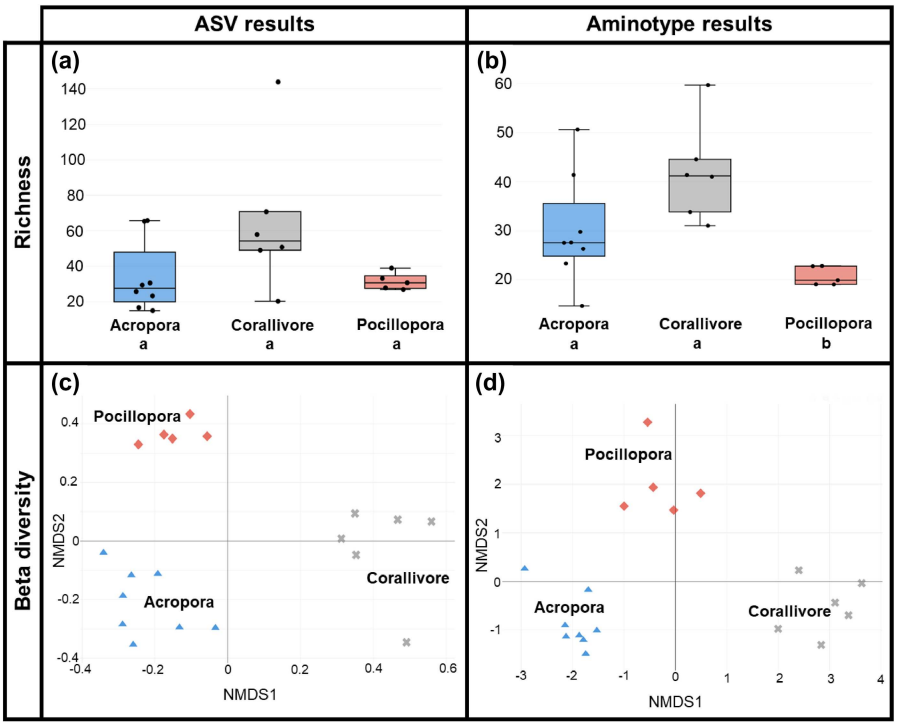

FIGURE 5 vAMPirus-generated dinoRNAV major capsid protein gene ASV and aminotype alpha (a, b) and beta (c, d) diversity results from stony coral colonies (*Acropora* sp., *Pocillopora* species complex) and corallivorous (coral-eating) fish faeces. Plots include three sample types: (1) *Acropora* biopsies (blue, triangle), (2) Corallivore faeces (grey, x), and (3) *Pocillopora* biopsies (red, diamond). Letters beneath *x* axis labels on richness box plots (I, II) indicate statistically different groups. ASV and aminotype based NMDS plots (III, IV) were generated with Bray Curtis distances (stress values of 0.04 and 0.03, respectively).

in at least some species of coral holobionts, and this difference is more readily detected with aminotype-based analyses (as ASV-based analyses may contain more 'noise' due to errors arising during RNA virus replication). This use case illustrates the potential benefits of running nucleotide and protein-based amplicon analyses in tandem when testing hypotheses regarding virus community diversity and dynamics. Furthermore, both ASV and aminotypes differed significantly in composition according to dinoRNAV reservoir (anosim with Bray Curtis distances, $R=0.99$, $p<0.01$; Figure 5c,d), although some overlap (14%, 26 of 190 aminotypes) among dinoRNAV communities was observed (Figure S6). Overall, this vAMPirus-based analysis of RNA virus amplicon sequencing data further corroborates that dinoRNAV communities differ across reef reservoirs (Grupstra et al., 2022; Montalvo-Proaño et al., 2017; Howe-Kerr et al., 2023; Figure 5) and generates a new hypothesis to be tested in future studies: corallivorous fishes are environmental hotspots of dinoRNAV diversity on reefscapes.

5 | DISCUSSION

Targeted gene sequencing is increasingly being applied to explore spatiotemporal patterns of viral diversity (Adriaenssens & Cowan, 2014; Finke & Suttle, 2019; Frantzen & Holo, 2019; Grupstra et al., 2022; Gustavsen & Suttle, 2021; Howe-Kerr et al., 2023; Li et al., 2018; Montalvo-Proaño et al., 2017; Prodinger et al., 2020; Short et al., 2010; Tong et al., 2016). The field of virology can now greatly benefit from the development of readily standardizable and reproducible pipelines for analysing amplicon sequence datasets. Here, we present vAMPirus; a freely available, powerful, and flexible bioinformatics tool that streamlines the processing, analysis and visualization of virus gene amplicon data. The availability of diverse bioinformatics approaches and tools within the vAMPirus program (e.g. ASV calling, clustering, translation, phylogenetic clustering) empowers the user to adapt and set informed standards for their study system and easily share these standards with colleagues. With a user-friendly design and robust documentation, vAMPirus democratizes comprehensive virus amplicon sequencing analyses, making it a timely and valuable tool for virologists.

To inform virus amplicon data analyses, virologists have primarily relied on pipelines and tutorials geared towards bacterial or microeukaryote amplicon data (e.g. mothur (Schloss, 2020) and QIIME2 (Bolyen et al., 2019)). Although valuable insights have been made using these resources, an accessible virus-focused amplicon analysis pipeline will advance the field by offering via (1) automated pipelines that standardize approaches for viral amplicon analyses (e.g. ASV and aminotype calling); (2) non-cluster-based alternatives to partitioning virus gene sequences (e.g. MED and phylogrouping); and (3) virus-focused taxonomy databases. Virus amplicon analyses have traditionally applied de novo clustering of marker gene sequences into de novo OTUs based on a percent identity value (i.e. 97% nucleotide identity, Callahan et al., 2017). However, clustering virus

amplicons into biologically accurate de novo OTUs is challenging as the optimal clustering percentage is often unknown. vAMPirus provides users with the opportunity to transition from traditional de novo OTUs in virus amplicon sequencing analyses to using ASVs and aminotypes. We have illustrated here that ASV and aminotype-based analyses generally recapitulate findings generated via de novo OTU-based analyses (Figures 3 and 4; Table S1), while enabling reproducibility and cross-study comparisons (Callahan et al., 2017). Running analyses of amino acid and nucleotide sequence data in tandem, which is possible in vAMPirus, can aid in resolving virus phylogenies and reveal non-synonymous mutations that indicate virus protein property variability within a community (DeFilippis & Villarreal, 2000). This synergistic approach has been effective in developing dinoRNAVs and their dinoflagellate hosts (family Symbiodiniaceae, endosymbionts of stony corals) as a nascent study system. To characterize dinoRNAVs, studies have used the *mcp* gene, which has a high mutation rate and is hypothesized to be important in host cell attachment (Tomaru et al., 2004). vAMPirus aminotyping uncovered non-synonymous mutations in dinoRNAV *mcp* sequences, which may represent phenotypic differences that correlate with the distribution of host lineages across reefs (Grupstra et al., 2022; Howe-Kerr et al., 2023, this study). Aminotyping also effectively reduced noise from high mutation rates in ASV results, revealing temperature-driven increases in dinoRNAV infection productivity and community diversity across time and space (Grupstra et al., 2022; time only, Howe-Kerr et al., 2023). By making viral protein sequence analyses readily accessible in an amplicon sequence analysis workflow, vAMPirus helps reveal biological patterns in DNA and highly mutable RNA virus lineages by increasing signal-to-noise ratio in results (through collapse of synonymous nucleotide mutations, Wernersson & Pedersen, 2003).

The increasing application of amplicon sequencing to the study of microbial diversity and dynamics has spurred efforts to improve the proficiency of tools that parse marker gene data. Such tools include the programs TreeCluster (Balaban et al., 2019) and oligotyping (Eren et al., 2015), which were developed as de novo clustering alternatives for partitioning genetic sequences into distinct units. In vAMPirus, these programs are utilized to assign ASVs and aminotypes to phylo- or MED groups based on user-set criteria (see Section 2.2.2). Assignment of ASV/aminotype sequences to groups rather than use of cluster representative sequences in analyses (such as, in the case of de novo OTUs and cASVs, Callahan et al., 2017) is done by vAMPirus to maintain reproducibility and comparability of results, while still permitting virus sequence classification into phylogenetically or ecologically distinct groups. These grouping approaches are instrumental for investigators because they can expose underlying patterns obscured by high sequence diversity (e.g. lactococcal phage phylogrouping results, Section 3, Figure 4). Phylogeny-based sequence clustering with TreeCluster has been applied to assess the diversity of microorganisms (and barley, Chen et al., 2022) and has been used to resolve virus transmission dynamics (HIV, Balaban et al., 2019; SARS-CoV-2, Plyusnin et al., 2022) and phylogenies (Ni et al., 2023). However, TreeCluster has yet to be commonly employed in virus amplicon analysis pipelines. The inclusion of TreeCluster in the vAMPirus pipeline also opens the door to epidemiological insights, such as virus genetic linkage, transmission dynamics and subpopulation mixing from viral datasets (Balaban et al., 2019; Bezemer et al., 2015; Eshleman et al., 2011; Hué et al., 2014). Similarly, the program oligotyping developed by Eren et al. (2015) has been applied extensively to investigate microorganism diversity from marker gene data (cited 332 times as of 2 February 2023, Web of Science). However, only one published study has applied Minimum Entropy Decomposition sequence clustering with oligotyping to virus amplicon data (see Needham et al., 2017). The MED grouping with oligotyping option provided by vAMPirus is a powerful approach for deciphering virus community diversity because it enables the grouping of sequences based on potential physiologically and/or ecologically relevant similarities. For example, users can identify gene sequence positions with non-synonymous mutations via aminotyping and then specify these positions in MED grouping to partition sequences into units of similar protein phenotypes (i.e. host cell attachment; see Harvey et al., 2021). While the MED grouping with oligotyping offers an avenue for dissecting virus community diversity, challenges such as its computational intensity, the requirement for high-quality sequences, and its primary optimization for microbial marker genes/communities necessitate careful consideration and possible adaptations when applying it to virology (discussed further in vAMPirus help documentation https://tinyurl.com/vAMPirusMED). The option to incorporate cutting-edge bioinformatic approaches, such as phylogrouping and MED grouping, into analyses of virus amplicon data makes vAMPirus a highly useful 'raw-reads-to-results' environmental virology workflow.

vAMPirus is an easy-to-use, open-source and flexible tool that streamlines and simplifies the process of analysing viral amplicon data. vAMPirus is designed to be community-driven; new features and programs (e.g. built-in lineage specific configuration files or databases, new bioinformatic tools) can easily be implemented at the request of investigators or when advances in best practices are made/advanced. vAMPirus advances studies of viral community diversity by facilitating informed analyses of amplicon sequence data with its DataCheck and Analyze pipelines in a standardized and reproducible manner.

AUTHOR CONTRIBUTIONS

AJV, CBG, LHK conceived of the program with support from AMSC; CBG and LHK contributed R code used in the vAMPirus reports; RERV contributed R code and helped execute vAMPirus incorporation into Nextflow; CBG, LHK and AMSC processed samples and generated the RNA virus dataset; AJV designed the pipelines with input from CBG and LHK; AJV wrote bash and R code used in the program, analysed data, and wrote the initial draft of the manuscript, with contributions by all authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no financial conflict of interest with the content of this article.

DATA AVAILABILITY STATEMENT

Source code, scripts and help documentation are available online at github.com/aveglia/vAMPirus. RNA virus sequencing libraries are available on NCBI SRA associated with the BioProject PRJNA923642 as well as in the vAMPirus Analysis Repository (doi.org/10.5281/zenodo.7574173). All non-read files required to reproduce all analyses and results described in this manuscript can be found on the vAMPirus Analysis Repository (doi.org/10.5281/zenodo.7574173).

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