antiSMASH 4.0-improvements in chemistry prediction and gene cluster boundary identification

Blin, Kai; Wolf, Thomas; Chevrette, Marc G.; Lu, Xiaowen; Schwalen, Christopher J.; Kautsar, Satria A.; Suarez Duran, Hernando G.; de Los Santos, Emmanuel L. C.; Kim, Hyun Uk; Nave, Mariana; Dickschat, Jeroen S.; Mitchell, Douglas A.; Shelest, Ekaterina; Breitling, Rainer; Takano, Eriko; Lee, Sang Yup; Weber, Tilmann; Medema, Marnix H.

Published in:
Nucleic Acids Research

Link to article, DOI:
10.1093/nar/gkx319

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):

DTU Library
Technical Information Center of Denmark

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
antiSMASH 4.0—improvements in chemistry prediction and gene cluster boundary identification

Kai Blin¹, Thomas Wolf², Marc G. Chevrette³, Xiaowen Lu⁴, Christopher J. Schwalen⁵, Satria A. Kautsar⁴, Hernando G. Suarez Duran⁴, Emmanuel L. C. de los Santos⁶, Hyun Uk Kim¹,⁷, Mariana Nave⁸, Jeroen S. Dickschat³, Douglas A. Mitchell⁵,¹⁰, Ekaterina Shelest², Rainer Breitling¹¹, Eriko Takano¹¹, Sang Yup Lee¹,⁷, Tilmann Weber¹,* and Marnix H. Medema⁴,*

¹Novo Nordisk Foundation Center for Biosustainability, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark, ²Leibniz Institute for Natural Product Research and Infection Biology—Hans-Knöll-Institute, 07745 Jena, Germany, ³Laboratory of Genetics, University of Wisconsin—Madison, Madison, WI 53706, USA, ⁴Bioinformatics Group, Wageningen University, 6708PB Wageningen, Netherlands, ⁵Department of Chemistry, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA, ⁶Warwick Integrative Synthetic Biology Centre, University of Warwick, Coventry CV4 7AL, UK, ⁷Department of Chemical and Biomolecular Engineering & Bioinformatics Research Center, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea, ⁸Faculty of Sciences, University of Lisbon, 1749-016 Lisbon, Portugal, ⁹Kekulé-Institute of Organic Chemistry and Biochemistry, University of Bonn, 53121 Bonn, Germany, ¹⁰Carl R. Woese Institute for Genomic Biology, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA and ¹¹Manchester Synthetic Biology Research Centre (SYNBIOCHEM), Manchester Institute of Biotechnology, University of Manchester, Manchester M1 7DN, UK

Received February 25, 2017; Revised April 07, 2017; Editorial Decision April 12, 2017; Accepted April 13, 2017

ABSTRACT

Many antibiotics, chemotherapeutics, crop protection agents and food preservatives originate from molecules produced by bacteria, fungi or plants. In recent years, genome mining methodologies have been widely adopted to identify and characterize the biosynthetic gene clusters encoding the production of such compounds. Since 2011, the ‘antibiotics and secondary metabolite analysis shell—antiSMASH’ has assisted researchers in efficiently performing this, both as a web server and a standalone tool. Here, we present the thoroughly updated antiSMASH version 4, which adds several novel features, including prediction of gene cluster boundaries using the ClusterFinder method or the newly integrated CAS-SIS algorithm, improved substrate specificity prediction for non-ribosomal peptide synthetase adenylation domains based on the new SANDPUMA algorithm, improved predictions for terpene and ribosomally synthesized and post-translationally modified peptides cluster products, reporting of sequence similarity to proteins encoded in experimentally characterized gene clusters on a per-protein basis and a domain-level alignment tool for comparative analysis of trans-AT polyketide synthase assembly line architectures. Additionally, several usability features have been updated and improved. Together, these improvements make antiSMASH up-to-date with the latest developments in natural product research and will further facilitate computational genome mining for the discovery of novel bioactive molecules.

INTRODUCTION

Natural products, also referred to as secondary or specialized metabolites, are the basis of many drugs and are also important molecules for agricultural and nutritional applications; moreover, they play key roles in scientific research as chemical probes to study many aspects of molecular and cellular biology. The observation that the genomes of many microorganisms contain multiple biosynthetic gene clusters (BGCs) that code for the production of such molecules has led to a paradigm shift in natural products research: within the last 10 years, genome mining has been established as an important technology complementing the bioassay- and chemistry-driven classical natural products discovery process (1). This fundamental change was supported by the development and public availability of various genome min-
ing software tools that are usable by wet-lab microbiologists and chemists (as reviewed in (2–4)), such as NP.searcher (5), antiSMASH (6–8), NaPDoS (9) and recently PRISM/GNP (10,11).

The comprehensive open-source BGC mining platform antiSMASH (6–8) was first released in 2011 and has been regularly updated with extended functionality. antiSMASH facilitates the mining of bacterial and fungal genomes and is tightly interconnected with plantiSMASH, a new variant for BGC mining in plants (12), the antiSMASH database (13) and the Minimum Information on Biosynthetic Gene Cluster (MIBiG) repository of experimentally characterized BGCs (14).

Here, we report version 4 of antiSMASH, which includes several major extensions, such as gene cluster boundary prediction for fungal BGCs, improved chemistry predictions for terpene, ribosomal peptide and non-ribosomal peptide BGCs, comparative alignment of trans-AT polyketide synthase (PKS) assembly lines and TTA codon annotation. Moreover, an improved user interface was introduced, along with several other usability and efficiency improvements. The public antiSMASH web server is freely accessible at http://antismash.secondarymetabolites.org.

NEW FEATURES AND UPDATES

Improved prediction of gene cluster boundaries. Estimating the boundaries of BGCs is a continuing challenge for genome mining tools. Traditionally, antiSMASH has opted for a ‘greedy’ approach by design, in order to ensure a greater likelihood of including all pertinent biosynthetic genes. The rationale behind this was that expert users would be better at estimating cluster boundaries than automated algorithms would. However, for certain purposes, it is still highly beneficial for users to review a computer-assisted estimate of where a BGC may start and end. For this reason, antiSMASH has now added two methods to predict the boundaries of BGCs. For fungal genomes, the Cluster Assignment by Islands of Sites (CASSIS) algorithm (15) is used for this purpose, which identifies genes within the BGC that share a common pathway-specific regulatory motif (Figure 1). Additionally, for both bacterial and fungal genomes, the user can now choose to use the ClusterFinder algorithm (16) to estimate cluster boundaries based on frequencies of locally encoded protein domains detected by Pfam (17) (based on these being either more or less BGC-like). If the user selects one of the BGC boundary prediction options (ClusterFinder for bacteria and fungi, CASSIS for fungi only), the extents of the predicted cluster region are displayed as bars above the BGC and also annotated in the GenBank files that can be downloaded.

New algorithms for non-ribosomal peptide and terpene chemistry prediction. Since the first version of antiSMASH, three algorithms have been used within the pipeline to predict the substrate specificities of non-ribosomal peptide synthetase (NRPS) adenylation (A) domains: the support-vector machine (SVM) and active-site motif (ASM) prediction methods from NRPSPredictor2 (18) and the profile HMM (pHMM)-based method from Minowa et al. Since then, several new algorithms have been published to predict A-domain specificity (19–21). More recently, Chevrette et al. (manuscript in review) substantially expanded the training sets for these algorithms, introduced an additional (phylogenetics-based) algorithm (PrediCAT), benchmarked all algorithms systematically and constructed an ensemble prediction method (called SANDPUMA) that outperformed each method individually. To benefit from the latest insights in this field, we have now replaced the previ-
ous prediction algorithms with the SANDPUMA predic-
tions; these provide not only the ensemble outputs, but also
the individual outputs of the underlying SVM, ASM, Pred-
iCAT and pHMM algorithms. Since the benchmark com-
parison had shown the Minowa method (22) to be the least
reliable of all previously published methods, this algorithm
was judged to be uninformative and has been removed from
the antiSMASH pipeline.

In addition to the prediction of non-ribosomal peptide
chemistry, antiSMASH now also provides chemical struc-
ture predictions for the products of bacterial terpene syn-
thases (23). To this end, a terpene cyclase-specific version of
PrediCAT (see Supplementary Figure S1 and Table S1) has
been included, to predict terpene cyclization patterns (such
as 1,6-, 1,10- or 1,11 cyclizations) based on phylogenetic re-
lationships with known enzymes from a documented refer-
ence set of terpene cyclases: when a query enzyme forms a
monophyletic clade with enzymes with a known cyclization
chemistry, this cyclization pattern is assigned to the query as
a prediction. These predictions (see Supplementary Figure
S1 for accuracy assessment) are then reported alongside the
name of and sequence identity to the most closely related
experimentally characterized homolog. It should be noted
that the predictions are only performed for those terpene
BGCs that encode mono-, sesqui- or diterpene cyclases
(Pfams PF01397 and/or PF03936) and not for those that
(only) encode phytone synthases, tetraterpene cyclases, ox-
idosqualene cyclases, tryptophan dimethylallyltransferases,
geranylgeranyl diphosphate (GGPP) synthases and/or ly-
copene cyclases.

Improved RiPP BGC identification and structure prediction.
Ribosomally synthesized and Post-translationally modi-
ﬁed Peptides (RiPPs) constitute a growing area of natu-
rnal products research. antiSMASH supports researchers in
predicting 15 distinct classes of RiPP BGCs. Previously,
antiSMASH predicted only lanthipeptide precursors us-
ing a relatively limited pHMM-based approach. The cur-
rent version of antiSMASH now provides a more sophis-
ticated prediction and classiﬁcation for class I lanthipep-
tides as well as lasso peptides, sactipeptides and thiopep-
tides. Given that RiPPs start as gene-encoded precursor
peptides prior to post-translational modiﬁcation, amino
acid sequence prediction provides a wealth of information
regarding the structure of the ﬁnal product. However, the
open-reading frames (ORFs) encoding these peptides are
often overlooked by automated analysis and can be highly
sequence variable, necessitating the need for current precu-
sor identiﬁcation methods.

To assist in identifying the precursor peptide-encoding
gene, antiSMASH now utilizes the algorithm from the
genome-mining platform Rapid ORF Description and
Evaluation Online (RODEO) (24), which uses a combina-
tion of heuristic scoring, SVM and motif analysis to eval-
uate all candidate precursor peptides in a putative RiPP
BGC. To broaden its applicability, the RODEO algorithm
was extended to perform precursor prediction not only for
lasso peptides, but also for thiopeptides, class I lanthipep-
tides and sactipeptides (see Supplementary Text 1 and Fig-
ures S2–4). When submitting an annotated nucleotide se-
quence to antiSMASH, the algorithm evaluates small genes
that are already part of this annotation, as well as all other
small ORFs in intergenic regions across the predicted clus-
ter, in order to mitigate issues with gene prediction.

For the RiPP classes analyzed by the RODEO algorithm,
antiSMASH reports: (i) the respective class of RiPP (e.g.
lasso peptide or sactipeptide, etc.), (ii) a predicted leader
peptide cleavage site and (iii) any potential C-terminal pro-
teolytic processing. Given the post-translational simplic-
ty of lasso peptides, a molecular mass is also calculated,
accounting for the number of disulfide bridges. For thiopep-
tides, the macrocycle size and potential amidation are pre-
dicted as well. Molecular weight predictions are not given
for the other RiPP subclasses owing to their extensive and
variable post-translational modiﬁcations.

Trans-AT PKS domain alignments. Several key classes of
natural products are produced by multimodal enzymatic
assembly lines. Standard similarity searches (as performed
in antiSMASH’s ClusterBlast module) do not reveal ma-
jor insights between the natural product structures and the
genes for the corresponding multidomain proteins that en-
code their biosynthetic enzymes. In order to better address
this issue, we have now included an assembly line align-
ment method for trans-AT PKS (E. Helfrich, X. Lu et al.
manuscript in preparation), which uses reference phyloge-
nies of ketosynthase (KS) domains to assign KS domains
from identiﬁed gene clusters into clades that correspond to
a certain type of polyketide chemistry. Based on this classi-
fication, the encoded assembly line is then aligned to ref-
ence assembly lines from known BGCs in MIBiG (14)
based on a distance metric that involves the Jaccard in-
dex, Goodman- Kruskal gamma function and domain dupli-
cation index of KS domain clades at empirically deter-
mined weights of 0.5, 0.25 and 0.25, respectively (see also
(25)). The assembly lines that are most closely related to the
query are then selected and clustered using Unweighted Pair
Group Method with arithmetic mean clustering with the
same metric and displayed in a visual alignment, in which
each KS domain clade is annotated with a distinct color
and a text description of the associated chemistry (Figure
2). This analysis allows for a rapid assessment of biochemical
relationships between the products of these assembly
lines, in order to identify new variants of known molecules
or to ﬁnd novel polyketide scaffolds.

TTA codon annotation. Streptomyces and related gen-
ergia are important producers of clinically used antibiotics,
such as tetracyclines or erythromycin, or drugs to treat
parasitic worms such as avermectin. These bacteria have
GC-contents of >70% and thus a skew toward higher GC
triplets in their codon usage. While genes involved in pri-
mary metabolism almost exclusively use CTC codons to
code for Leu, key genes in secondary metabolism and cell
differentiation often contain TTA codons. As the expres-
sion of the TTA-codon speciﬁc Leu-tRNA-gene blda is
tightly controlled and the Leu-tRNA only accumulates in
later stages of growth, this offers an additional level of regu-
lation (26–28). The expression of the BGCs therefore does
not only require activation at the transcriptional level, but
also the presence of the TTA-speciﬁc Leu-tRNA. This must
be considered, for example, for heterologous BGC expres-
sion in other streptomycete hosts or metabolic engineering approaches. Therefore, a new feature was included in antiSMASH version 4 to automatically scan all BGCs for the presence of TTA codons and annotate these in the graphical cluster overview and the GenBank/EMBL result files.

**Usability and efficiency improvements.** antiSMASH comes with an updated, larger ClusterBlast database for comparative gene cluster analysis. In order to keep the runtime of the ClusterBlast analysis at acceptable levels with the much larger database, antiSMASH now uses the BLAST-compatible DIAMOND algorithm (29) to calculate results for ClusterBlast (against all ±220,000 BGCs currently detected in NCBI GenBank) and KnownClusterBlast (against experimentally characterized BGCs from MIBiG (14)). ClusterBlast results are now cross-referenced to the antiSMASH database (13), whenever present there, through hyperlinks on the matched clusters; this allows researchers to quickly get a more complete view of these BGCs. Also, for each gene in a predicted gene cluster, an individual BLAST search is now automatically run against all proteins encoded in BGCs deposited in MIBiG (14); this helps researchers to predict functions of individual genes based on similarity of their encoded amino acid sequence to those of experimentally characterized proteins, even when the rest of the surrounding gene clusters are not similar.

In order to simplify selecting the correct input settings, separate submission pages were created for fungal sequences (http://fungismash.secondarymetabolites.org/) and plant sequences (http://plantismash.secondarymetabolites.org/). The main antiSMASH website is now focused on bacterial and archaeal sequences. The metabolic modeling functionality along with an EC number prediction option that were introduced in antiSMASH version 3 were removed again, as they led to extremely long run times and high server load. An updated version with improved reaction rules for secondary metabolite biosynthetic pathways will be released as a separate, but still closely linked program.

In addition to GenBank- and EMBL-formatted files, gene annotations can now also be added to FASTA sequences by also uploading a GFF3-formatted file. To assist job submission and retrieval from third-party tools running upstream or downstream analyses such as the CRISPR single guide RNA finding tool CRISPy-web (30) or the Antibiotics Resistance Target Seeker service (31), the antiSMASH web component now supports a REST-like (32) web API.

**CONCLUSIONS AND FUTURE PERSPECTIVES**

With the new features now introduced (Table 1), the antiSMASH framework continues to improve through the concerted action of researchers in the natural products community. A number of additional features are still in development, including application of the visual assembly line alignments to NRPSs, detailed gene cluster boundary prediction through phylogenetic profiling and detection of putative resistance genes inside BGCs.
Table 1. Overview of analyzes integrated into antiSMASH

<table>
<thead>
<tr>
<th>Rule-based detection of BGCs</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aminocyclitols</td>
<td>Microcin</td>
</tr>
<tr>
<td>Cyclodiene</td>
<td>Micrococcin</td>
</tr>
<tr>
<td>Polyketide</td>
<td>None-Esterified peptides</td>
</tr>
<tr>
<td>Nucleoside</td>
<td>Non-ribosomal peptides</td>
</tr>
<tr>
<td>Oligosaccharide</td>
<td>Nucleosides</td>
</tr>
<tr>
<td>Others</td>
<td>Oligosaccharides</td>
</tr>
<tr>
<td>Peptidoglycan</td>
<td>Peptides</td>
</tr>
<tr>
<td>Phospholipid</td>
<td>Phospholipids</td>
</tr>
<tr>
<td>Phosphonate</td>
<td>Polyaminoamino acids</td>
</tr>
<tr>
<td>Polyketide</td>
<td>Polyketide Synthase (PKS)</td>
</tr>
<tr>
<td>Type-I PKS</td>
<td>Type II PKS</td>
</tr>
<tr>
<td>Type II PKS</td>
<td>Type III PKS</td>
</tr>
</tbody>
</table>

Rule-independent detection of BGCs

<table>
<thead>
<tr>
<th>Domain structure of PKSs and NRPSs</th>
<th>PRISM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKS: AT specificity prediction</td>
<td>PRISM</td>
</tr>
<tr>
<td>Identification of conserved active site motifs, stereochemistry-determining motifs</td>
<td>PRISM</td>
</tr>
<tr>
<td>Prediction of core chemical structure (PKPs, PKS, laeobides, thioesters, peptides)</td>
<td>PRISM</td>
</tr>
<tr>
<td>SmPGO secondary metabolism-related gene family prediction</td>
<td>PRISM</td>
</tr>
</tbody>
</table>

TTA codon annotation for arthomycetes

Improved prediction of gene cluster borders for fungal BGCs (CASSIS)

Genome-wise analyses

<table>
<thead>
<tr>
<th>Protein family analysis (PFAM) search</th>
<th>antismash.db</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genome comparisons</td>
<td>MBG repository</td>
</tr>
<tr>
<td>SubClusterBlast</td>
<td>NCBI BLAST+</td>
</tr>
<tr>
<td>KsownClusterBlast</td>
<td>NaPoiS</td>
</tr>
<tr>
<td>TransAT:PKS Domain Alignments</td>
<td>Name</td>
</tr>
</tbody>
</table>

Links to other Web-resources

<table>
<thead>
<tr>
<th>antismash.db</th>
<th>Genome comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genome comparisons</td>
<td>Output file formats</td>
</tr>
<tr>
<td>ClusterBlast</td>
<td>Genbank</td>
</tr>
<tr>
<td>Identification of similar clusters in sequence genomes</td>
<td>EMBL</td>
</tr>
<tr>
<td>SubClusterBlast</td>
<td>EMBL</td>
</tr>
<tr>
<td>Identification of conserved operons with known function</td>
<td>IselectNL</td>
</tr>
<tr>
<td>KsownClusterBlast</td>
<td>Tab-delimited text files</td>
</tr>
<tr>
<td>Identification of similar characterized gene clusters</td>
<td>Input file formats</td>
</tr>
<tr>
<td>TransAT:PKS Domain Alignments</td>
<td>FASTA (nucleotide or protein)</td>
</tr>
<tr>
<td></td>
<td>FASTA + SPF</td>
</tr>
<tr>
<td></td>
<td>Genbank / Genpept</td>
</tr>
<tr>
<td></td>
<td>EMBL</td>
</tr>
</tbody>
</table>

With regard to chemistry prediction of the products of NRPSs and PKSs, we have opted to be conservative for the moment. The recently introduced PRISM pipeline (11) does a great job of automatically predicting a wide range of possible products of each BGC, which facilitates automated matching to large-scale metabolomic data. However, the majority of antiSMASH users still rely on manual comparison of BGCs with smaller-scale experimental data; we feel that this approach benefits more from reliable predictions of substructures and substrate specificities (and refraining from making lower-confidence combinatorial predictions). In this respect, PRISM and antiSMASH offer complementary functionalities and the user can opt to use either pipeline based on the intended research purposes.

We continue to strive for interoperability with other services. For example, antiSMASH predictions are also available through the Joint Genome Institute’s IMG-ABC (33) as well as Genoscope’s framework MicroScope (34); connections to EFI-EST (35) and other tools are being investigated. Also, we remain committed to collaborating with other researchers worldwide and invite expert feedback as well as technical contributions from the community to improve this important piece of software.

**AVAILABILITY**

antiSMASH is available from http://antismash.secondarymetabolites.org/. This website is free and open to all users and there is no login requirement. Source code is available from https://bitbucket.org/antismash/antismash/.

**SUPPLEMENTARY DATA**

Supplementary Data are available at NAR Online.

**FUNDING**

Novo Nordisk Foundation (to S.Y.L., T.W.); The Netherlands Organization for Scientific Research (NWO) VENI Grant [863.15.002 to M.H.M.]; Graduate School for Experimental Plant Sciences (EPS) (to M.H.M.); Ministry of Science, ICT and Future Planning through the National Research Foundation (NRF) of Korea [NRF-2012M1A2A202656] to H.U.K., S.Y.L.]; International Leibniz Research School for Microbial and Molecular Interactions (ILRS), as part of the excellence graduate school Jena School for Microbial Communication (JSMC), supported by the Deutsche Forschungsgemeinschaft (DFG) [to T. Wo.]; Collaborative Research Centre ChemBioSys (CRC 1127 ChemBioSys), by the DFG (to E.S.); NIH National Research Service Award [T32 GM008505 to M.G.C.]; David and Lucile Packard Fellowship for Science and Engineering (to D.A.M.); Department of Chemistry at the University of Illinois at Urbana–Champaign Fellowship (to C.J.S.); NIH Chemical Biology Interface Training Program Fellowship [T32 GM070421 to C.J.S.]; Google Summer of Code grant (to M.N.); Warwick Integrative Synthetic Biology Centre (WISB), and Manchester Synthetic Biology Research Centre (SYNBIOCHEM) funded under the UK Research Councils’ ‘Synthetic Biology for Growth’ programme [BB/M017982/1 (WISB), BB/M017702/1 (SYNBIOCHEM)]. Funding for open access charge: Netherlands Organization for Scientific Research (NWO).

**Conflict of interest statement.** None declared.

**REFERENCES**