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McCaughey, Catherine S.; Santen, Jeffrey A.; Hooft, Justin J.J.; Medema, Marnix H.; Linington, Roger G.
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An isotopic labeling approach linking natural products with biosynthetic gene clusters

Catherine S. McCaughey, Jeffrey A. van Santen, Justin J. van der Hooft, Marnix H. Medema and Roger G. Linington

Major advances in genome sequencing and large-scale biosynthetic gene cluster (BGC) analysis have prompted an age of natural product discovery driven by genome mining. Still, connecting molecules to their cognate BGCs is a substantial bottleneck for this approach. We have developed a mass-spectrometry-based parallel stable isotope labeling platform, termed IsoAnalyst, which assists in associating metabolite stable isotope labeling patterns with BGC structure prediction to connect natural products to their corresponding BGCs. Here we show that IsoAnalyst can quickly associate both known metabolites and unknown analytes with BGCs to elucidate the complex chemical phenotypes of these biosynthetic systems. We validate this approach for a range of compound classes, using both the type strain Saccharopolyspora erythraea and an environmentally isolated Micromonospora sp. We further demonstrate the utility of this tool with the discovery of lobosamide D, a new and structurally unique member of the family of lobosamide macrolactams.

Many of the current approaches used for integrating metabolomic and genomic datasets are based on tandem mass spectrometry (MS/MS) fragmentation spectra. While these approaches have been successful in identifying new chemistry and streamlining metabolite discovery, they do not directly determine the biosynthetic origins of individual compounds through targeted labeled feedstock addition and compound isolation. However, these approaches are not appropriate for system-wide studies because of the need to isolate and acquire NMR spectra or specific activities for each individual compound of interest. Stable isotope labeling has also been used extensively in studies related to primary metabolism and metabolic flux analysis, for which several open-source mass spectrometry (MS) data processing packages have been developed, including XCMS and mzMatch-ISO. However, although these platforms are capable of annotating metabolites with stable isotope label incorporation, they do not directly determine the maximum degree of labeling for each metabolite in the sample or do not align compounds between experiments using a variety of different stable isotope labels, limiting their utility for connecting molecules to BGCs.

1Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, Canada. 2Bioinformatics Group, Wageningen University, Wageningen, the Netherlands. ✉e-mail: rliningt@sfu.ca

G enome sequencing has fundamentally changed the paradigm of natural product research and discovery. With advancing technology and decreasing costs, the accessibility of high-quality genome information has increased exponentially. Over the past decade, this accumulation of genome sequence data has inspired the development and refinement of computational tools for identifying BGCs, predicting structural elements of the compounds they produce, prioritizing novel BGCs or a combination thereof. With recent developments in the accessibility of these tools, BGC databases such as MIBiG and IMG-ABC will continue to grow in both size and value to the scientific community as annotations and experimental validation of chemical structures are updated. Community efforts such as the Natural Products Atlas and LOTUS databases also enhance our understanding of the ‘specialized metabolome’ by providing curated records linking structures to the taxonomy of their producing organisms.

Bacterial genome analysis is rapidly changing from an effort directed towards a handful of strains, to one focused on thousands of sequences. Large-scale comparisons of BGC families have proven to be powerful tools in leveraging these large datasets for natural product discovery. Advances in these computational tools for understanding BGCs have long been promoted as a mechanism to eliminate the most common complications of traditional natural product discovery and facilitate automated, high-throughput workflows. Although bioinformatics approaches are moving rapidly towards a global scale for BGC analysis, efforts to efficiently identify associated chemistry remain technically challenging and time-consuming.

Another major bottleneck in genome mining is that many organisms suffer from low or no expression of the BGCs of interest under laboratory conditions. Host engineering to optimize heterologous expression and various other strategies have addressed this challenge with some successes, but most approaches still face limitations in detecting and identifying cognate products. Consequently, new BGCs are typically identified at a higher rate than their associated chemistry because the field lacks tools to quickly establish connections between BGCs and the metabolites they produce.
To address these challenges, we have developed a new analytical platform, termed IsoAnalyst. This platform employs parallel stable isotope labeling (SIL) to categorize specialized metabolites in liquid fermentations based on biosynthetic precursor incorporation, and connects these molecules to candidate BGCs using annotated genome sequence data. Parallel fermentation of the test organism is performed in the presence of either an isotopically labeled precursor or a control culture containing the corresponding unlabeled precursor for a panel of SIL tracers (Fig. 1a; 24-well plates, one condition per column, four replicates per condition). Following workup and ultra-performance liquid chromatography mass spectrometry (UPLC–MS) analysis of all samples, the IsoAnalyst pipeline identifies unique MS features present in each condition, and compares mass isotopologue distributions between unlabeled and labeled conditions to determine the degree of labeling by each precursor (Fig. 1b). Experimental precursor incorporation patterns are then manually compared against the theoretical precursor incorporation rates derived from BGC annotations (Fig. 1c) to yield candidate BGC(s) responsible for the production of each labeled metabolite. This approach streamlines the categorization of analytes by their biosynthetic origin and reduces MS metabolic profiles to quickly delineate the complex phenotypes of BGCs. The IsoAnalyst package is freely available under an open access MIT software license (https://github.com/liningtonlab isoanalyst) and accepts data in a simple format compatible with most major mass spectrometry instrument vendors.

**Results**

**Parallel stable isotope labeling in microtiter plates.** IsoAnalyst was developed to permit flexibility in terms of SIL precursor selection. To demonstrate the scope of IsoAnalyst across a broad cross-section of biosynthetic classes, we selected four ‘generalist’ precursors for this study: [1-13C]acetate, [1-13C]propionate, [methyl-13C]methionine and [1-15N]glutamate. [1-13C]Acetate can be incorporated directly into polyketide products via malonyl-coenzyme A (malonyl-CoA), but can also be incorporated into other biosynthetic monomers such as amino acids through primary metabolism recycling (Extended Data Fig. 1). This makes [1-13C]acetate a valuable feedstock for labeling a wide cross-section of natural product classes but it also complicates data interpretation, as we discuss below. [1-13C]Propionate is predominately used for identifying polyketide pathways, due to its conversion to methylmalonyl-CoA, a common building block in type I and type II polyketide biosynthesis. [Methyl-13C]methionine was selected in order to label compounds methylated by S-adenosylmethionine (SAM). Finally, [1-15N]glutamate was selected to constitutively label all products containing nitrogen atoms.

To reduce costs and improve throughput, we developed a fermentation protocol using a minimal media in 24-well microtiter plates (Methods). To ensure robust and consistent labeling, we performed preliminary experiments to determine both the ideal concentration for each SIL feedstock condition (Supplementary Fig. 1; Methods) and the optimal timing for feedstock addition (Supplementary Fig. 2; Methods). Four replicate wells are inoculated for each SIL precursor...
condition and a matching unlabeled control condition containing the same precursor molecule with a natural isotopic abundance (Fig. 1a). All of these parallel experiments are inoculated on the same day with the addition of appropriate precursors and cultured for five days prior to extraction, UPLC–MS analysis, MS data analysis and precursor incorporation calculation (Methods).

**Erythromycin A SIL incorporation predicts BGC origin.** We performed the parallel SIL experiment described above with the erythromycin A producer *Saccharopolyspora erythraea* NRRL 23338 to first demonstrate how IsoAnalyst connects MS isotope patterns with substrates inferred from BGC data under ideal circumstances in which all substrates can be correctly deduced (Fig. 2). The biosynthesis of erythromycin A (1) has been studied extensively as a model system for modular polyketide synthases[36]. The macrolide core is formed by the condensation of one propionyl-CoA and six methylmalonyl-CoA units followed by glycosylation with the saccharides desosamine and mycarose[37] (Fig. 2a,b). [1-13C]Propionate is directly converted to the substrates propionyl-CoA and methylmalonyl-CoA, however the latter may also be labeled by [1-13C]acetate through conversion to the tricarboxylic acid (TCA) cycle intermediate succinyl-CoA (Extended Data Fig. 1). The indirect labeling of methylmalonyl-CoA by [1-13C]acetate is included in the BGC labeling prediction because we cannot differentiate analytically between direct and indirect SIL incorporation (Fig. 2a). Desosamine contains a tertiary dimethylamino group that is expected to be labeled by a single position in the [1-15N]glutamate condition, and two positions in the [methyl-13C] methionine condition. The mycarose unit has a single methylation position and is later methylated by an O-methyltransferase following attachment to the macrolide core (Fig. 2a). Initial observation of the MS data for erythromycin A showed appreciable labeling in all of the expected conditions (Fig. 2b). However, a reliable method to identify the largest isotopologue peak with detectable SIL incorporation was needed to directly compare these MS results with the predicted labeling pattern.

To systematically determine the extent of labeling in every feature detected in the MS metabolomics data, we developed a novel algorithm to determine the statistical confidence of SIL incorporation in MS features. This algorithm requires two input file types: a deisotoped feature list for each unlabeled precursor condition, and a centroided scan-by-scan MS peak list for each individual culture condition (labeled and unlabeled). The deisotoped feature list contains averaged m/z and retention time pairs for all features observed in at least three replicates. These features are used as ‘anchor points’ to extract the relevant isotopologue data for each peak from the scan-by-scan peak lists which are in turn used to determine the degree of isotopic labeling in each condition (Extended Data Fig. 2a and Methods).

IsoAnalyst determines the degree of isotopic labeling for each analyte by comparing the relative intensities of the first isotopologue peak (one 13C; M1) and the monoisotopic mass (all 12C; M0) in the unlabeled dataset with sequential pairs of peaks (for example, M1 versus M0, M2 versus M1, and so on) in the labeled dataset (Fig. 2c,d). To compare isotopologue ratios between unlabeled and labeled peaks we first plot the intensity of the M1 versus M0 peaks for each scan in the chromatographic peak and then derive the slope from the linear regression for these data (Extended Data Fig. 3). We next derive the slope value from analogous plots for each isotopologue pair in the labeled condition, continuing across the isotopologue distribution (Fig. 2c). This analysis is performed independently for all replicates of each labeling condition, giving four slope values per isotopologue pair. Starting with M1 and M0 we ask the question, ‘does this isotopologue ratio differ significantly from the M1 to M0 ratio of the same chemical species having a natural isotopic distribution?’ We answer this question by performing Welch’s two-tailed t tests between the M1 versus M0 peaks in the unlabeled condition and sequential isotopologue pairs in the labeled condition. Finally, we assume that for every position where this ratio is significantly greater than the M1:M0 ratio of the unlabeled feature, at least that many positions are enriched in that SIL condition (Fig. 2d and Methods). This analysis, therefore, does not define the precise number of biosynthetic precursors in the structure, but rather the minimum number of detectable incorporation events for each SIL feedstock in a given MS feature. A comparison of the results from the BGC substrate analysis and IsoAnalyst results for the [M+H]+ ion of erythromycin A (1) revealed that the observed labeling matched the predicted labeling in every SIL condition except [1-13C]acetate, which exhibited a lower degree of labeling due to the indirect incorporation into of methylmalonyl-CoA into the core polyketide building blocks that cannot be precisely predicted (Fig. 2e).

In total, four features were detected for 1, corresponding to different fragments of the same compound (Fig. 2f,g). The dehydrated fragment ion m/z 716.4565 had labeling patterns that matched the [M+H]+ ion, whereas smaller fragments showed decreased labeling from [methyl-13C]methionine due to the loss of the mycarose sugar subunit (Fig. 2f). IsoAnalyst, therefore, not only accurately detects SIL incorporation in MS features across multiple conditions, but can also group adducts and fragments that derive from the same compound, simplifying the interpretation of labeling data for complex samples.

**Predicted SIL incorporation in products of *S. erythraea* BGCs.** To apply the IsoAnalyst workflow to the full metabolome of *S. erythraea*, we first performed BGC mining on the full *S. erythraea* NRRL 2338 genome using antiSMASH v.5.2.0–8ecc354 (Methods). The antiSMASH output offers substrate predictions for a broad cross-section of biosynthetic classes using a suite of prediction algorithms including SANDPUMA[38], NRPSPredictor[239] and RODEO[40]. Using these predictions in combination with literature references from the MIBiG database[2], we obtained detailed substrate predictions for all annotatable BGCs in the genome (Supplementary Table 6; Methods). Each column of this table contains predicted substrate counts for a single gene cluster from a list of commonly encountered biosynthetic substrates predicted to be labeled by one or more SIL precursors. A detailed step-by-step protocol for deriving predicted substrates from antiSMASH-discovered BGCs can be found in Supplementary Note 2.

To relate substrate counts to isotopic labeling patterns, it is necessary to know the degree of labeling of each biosynthetic substrate by each SIL precursor. A substrate labeling table (Supplementary Table 1) was generated by considering the metabolic fate of each precursor in this organism. Of the SIL feedstocks used in this study, [1-13C]acetate is the most promiscuous due to its incorporation in the TCA cycle (Extended Data Fig. 1). Indirect incorporation of [1-13C]acetate into amino acids and other TCA-derived substrates is significant but variable under different metabolic conditions and therefore requires careful interpretation. By contrast, [1-15N]glutamate and [methyl-13C]methionine are expected to label only specific substrates. Finally, the [1-15N] glutamate SIL condition is intentionally designed to be promiscuous and labels all amino acids and other subunits derived from amino acids (Supplementary Table 1).

To predict the labeling patterns for each BGC, we integrated data from the curated antiSMASH output (Supplementary Table 6) and the substrate labeling table (Supplementary Table 1) to create a table of predicted precursor labeling for all BGCs in the genome (Table 1). Not all of the BGCs in the *S. erythraea* genome are as amenable to SIL incorporation in our experiment as erythromycin, which has SIL incorporation in all four conditions. Some well-characterized BGC classes, such as terpenes, do not have sufficient SIL incorporation across the conditions used in this experiment, whereas products of BGCs with partial predictions may be labeled under these
enzyme once attached to the core. Indirect labeling of methylmalonyl-CoA occurs by transformation of [1-13C]acetate through the TCA cycle (Extended
and their expected labeling. The mycarose subunit is methylated once prior to attachment to the polyketide core, and further methylated by a tailoring
overview of isoAnalyst results for erythromycin A (1).

| Expected | Observed |
|----------|----------|
| A | P | M | G | A | P | M | G |
| 1 | + | 1 |

Fig. 2 | Overview of IsoAnalyst results for erythromycin A (1). a. Diagram of the erythromycin BGC, the biosynthetic substrates predicted by antiSMASH
and their expected labeling. The mycarose subunit is methylated once prior to attachment to the polyketide core, and further methylated by a tailoring
enzyme once attached to the core. Indirect labeling of methylmalonyl-CoA occurs by transformation of [1-13C]acetate through the TCA cycle (Extended
Data Fig. 1). b. Structure of erythromycin A (1) showing the expected positions of SIL incorporation and MS of 1 under the four SIL conditions. c. Centroided
scan data for mass isotopologues of 1 from one unlabeled control replicate and one [1-13C]acetate labeled replicate plotted as m/z versus intensity.
d. Centroided scan-by-scan data from c plotted as ion intensity of neighboring isotopologues in each scan (that is, M1:M0, M2:M1 and so on). Only the
M1:M0 isotopologue ratio is plotted for the unlabeled sample replicate, while all neighboring isotopologue pairs are shown for the [1-13C]acetate sample
replicate. The table below shows the two-tailed Welch’s t test results comparing the slope of each isotopologue ratio in the [1-13C]acetate condition to
the M1:M0 isotopologue ratio of the unlabeled sample. The ratio of M4:M3 is the last isotopologue ratio with a significant P value (<0.05) and a negative
test statistic, indicating four significantly labeled positions of 1 in the [1-13C]acetate condition. The slope values for each isotopologue neighbor pair from
each replicate form the basis for the t tests. e. Isotopologue ratio analysis is repeated for the same feature in all four conditions and compared with the
expected labeling determined by BGC analysis. f. Four mass features representing adducts and fragments of 1, and the SIL incorporation detected for each.
g. Extracted ion chromatograms of the four features indicated in (f).
Table 1 | Biosynthetic gene cluster labeling prediction for S. erythraea

| Cluster | Type | A  | P  | M  | G  |
|---------|------|----|----|----|----|
| 25      | Lanthipeptide | 29 | 47 |
| 22      | Lanthipeptide  | 1+ |
| 28      | Lanthipeptide  | 1+ |
| 31      | Thiopetide     |    |
| 12      | NRPS           | 4  | 6  |
| 15b     | NRPS           | 9  | 7  |
| 24a     | NRPS           | 3  | 9+ |
| 2      | NRPS           | 2  | 2  |
| 6      | NRPS           | 2  | 2+ |
| 15a     | NRPS           | 1+ |
| 17      | NRPS           | 1+ |
| 11      | PKS–NRPS hybrid | 6 | 3 | 1 |
| 13a     | PKS–NRPS hybrid | 2 | 2 | 1 |
| 4      | Type I PKS     | 7  | 7 | 4 | 1 |
| 23      | Type I PKS     | 9  | 5  |
| 10      | Type I PKS     | 1  | 1  |
| 24b     | Type I PKS     | 1  | 1  |
| 9b      | Type I PKS     | 2+ |
| 32a     | Type I PKS     | 1+ | 1+ |
| 33a     | Type I PKS     | 1+ |
| 1b      | PKS            | 1+ | 1+ |
| 5a      | Type III PKS   | 5  |
| 27      | Other/type III PKS | 1+ | 1 |
| 26a     | Other PKS      | 1+ | 1  |
| 35b     | Other PKS/FAS  | 4  |
| 3       | Other PKS/FAS  | 1+ |
| 14      | Other PKS/FAS  |    |
| 8,16,18,20,21,24c,36 | Terpene |
| 29a     | Terpene        | 1  | 1  |
| 30      | Terpene/NRPS-like | 1+ |
| 15c     | Beta-lactone   |    |
| 7      | Indole         | 1  | 1  |
| 34      | Other          |    |

*BGCs meet two selection criteria, as indicated in the text. *BGCs meet one selection criteria, as indicated in the text. FAS, fatty acid synthase.

conditions but cannot be reliably associated without additional genetic analysis. We use two criteria to determine the likelihood of identifying the product of a BGC with the SIL precursors used in this study. First, the predicted product of a BGC should be labeled in two or more conditions, because it is not possible to differentiate products of related BGCs on the basis of labeling in a single condition. Second, the product must be labeled three or more times in at least one of the conditions, because minor SIL incorporation is likely to occur in off-target compounds involved in primary metabolism. In Table 1 and Supplementary Table 2, BGCs that meet both criteria or only one of the criteria are indicated.

SIL in S. erythraea reveals compounds from two distinct BGCs. The summary of SIL incorporation results from IsoAnalyst is initially generated by filtering for features that have detectable SIL incorporation in two or more feedstock conditions. This file is then manually interrogated to filter features based on chromatographic peak shape and signal intensity. Features were eliminated if either of these factors interfered with the accuracy of the SIL detection. IsoAnalyst identified 98 features in the S. erythraea extracts with SIL incorporation in two or more conditions. Sixty of these features derived from six compounds with very similar SIL incorporation patterns, including erythromycin A (1) (features represented by diamonds in Fig. 3).

All of the erythromycin BGC products identified had related labeling patterns in the [1-13C]acetate and [1-15N]propionate conditions due to the shared polyketide core (Fig. 3b,c). Complete labeling by [1-13C]propionate was detected in all six compounds, while there was slight variation in the detection of [1-15N]acetate incorporation. By contrast, labeling in [methyl-13C]methionine and [1-15N]glutamate varied between the six products, suggesting different degrees of decoration of the polyketide core (Fig. 3b,c). Erythronolide B (2) was not labeled by either [methyl-13C]methionine or [1-15N]glutamate, consistent with the proposed structure containing only the core macrocycle. 3-O-α-Mycarosyl-erythronolide B (MEB) (3) contained a single labeled position in [methyl-13C]methionine, consistent with the addition of the mycarose sugar, which contains a single site of SAM methylation. The additional methylation position in the mycarose moiety of 1 is derived from tailoring enzyme activity which occurs after the mycarose sugar is attached to the polyketide core (Fig. 3b). The identities of 1, 2 and 3 were confirmed by UPLC–MS coinjection with commercial standards and NMR analysis where applicable (Supplementary Figs. 3–13). The final three steps in the erythromycin pathway are performed in a variable order by tailoring enzymes35, resulting in the four related products, erythromycin A (1), B (4), C (5) and D (6) (Fig. 3c). We putatively identified 4, 5 and 6 on the basis of the detected m/z values and SIL incorporation patterns indicating glycosylation with desosamine, and O-methylation of the mycarose sugar moiety (Fig. 3c).

Six features with significant labeling in both [1-13C]acetate and [1-15N]glutamate, but no incorporation of either [1-13C]propionate or [methyl-13C]methionine, were also detected by IsoAnalyst (features represented by circles in Fig. 3a). BGC 15b is the only BGC that has predicted labeling which matches the labeling of this compound (Table 1 and Fig. 3a). BGC 15b was identified by antiSMASH as the siderophore erthrochelin BGC (Supplementary Table 6), suggesting the presence of the siderophore erthrochelin (7), previously isolated from S. erythraea46.

[1-13C]Acetate incorporation into 7 was predicted to occur a maximum of nine times, with six of these incorporation events occurring via labeling of the ornithine carbon skeleton (Fig. 3a). 25b Lanthipeptide 1

Application of IsoAnalyst to an environmental Micromonospora sp. We next applied the IsoAnalyst platform to a fully sequenced Micromonospora sp. isolate from our marine-derived Actinobacterial strain library44. We analyzed the full genome of this strain using antiSMASH and manually curated substrate predictions (Supplementary Table 7) as described above to produce
the predicted BGC labeling table (Supplementary Table 2). Parallel SIL culture, followed by MS analysis and data processing with the IsoAnalyst pipeline identified 246 MS features that were labeled in two or more SIL conditions. These were further filtered to 100 MS features based on chromatographic peak shape and signal intensity, as discussed above.

These 100 features could be grouped into two major compound classes based on their isotope labeling patterns (Fig. 4), both of which could be confidently linked to their respective BGCs. The first class possessed significant labeling by both [1-13C]propionate (1–2 positions) and [1-15N]glutamate (5–6 positions) (Fig. 4a). The only BGC in Supplementary Table 2 containing two or
more [1-13C]propionate labels and six or more [1-15N]glutamate labels is BGC 6. This hypothesis was supported by alignment with the other two SIL precursors, with significant labeling with [1-13C]acetate (2–4 positions) but no observed labeling with [methyl-13C]methionine (Fig. 4a). This group of labeled MS features was consistently associated with iron adducts and related fragment ions, suggesting a family of related siderophores. BGC 6 was predicted to produce a siderophore by antiSMASH, and had 100% match with the BGC responsible for producing desferrioxamines B (8) and E (9)43.

Fig. 4 | SIL incorporation and structures for selected labeled ions detected in the Micromonospora sp. metabolome. Label incorporation from feedstocks [1-13C]acetate (A), [1-13C]propionate (P), [methyl-13C]methionine (M) and [1-15N]glutamate (G) are shown. a, SIL incorporation in ions corresponding to desferrioxamine compounds (represented as gray circles). Open yellow circles on structures represent ambiguous labeling positions, where [1-13C]propionate may be incorporated into either position, but not both, due to the symmetry of succinate which can be interchanged with succinyl-CoA. b, SIL incorporation in ions corresponding to lobosamide compounds (represented as gray diamonds). c, SIL incorporation detected for an MS feature corresponding to the [M+H]+ ion of an unknown desferrioxamine compound. d, SIL incorporation detected for an MS feature corresponding to the [M+H]+ ion of an unknown lobosamide compound.

561.3607 [M+H]+

500.3015 [M+H]+
Enrichment of SIL in compound 8 was detected for all six nitrogens derived from lysine in the [1-15N]glutamate condition, four of the six expected subunits in the [1-13C]acetate condition and one of the two expected subunits in the [1-13C]propionate condition (Fig. 4a). Labeling by [methyl-13C]methionine was not detected in 8 or any related compounds. Six known desferrioxamine derivatives (8–13) were identified based on MS spectra, database matching and the manual interpretation of SIL patterns. The identities of all compounds were confirmed by coinjection with authentic standards (Extended Data Fig. 6 and Supplementary Figs. 14–19). Desferrioxamine E (9) and D2 (10) are cyclized derivatives of the ferrioxamine scaffold44, and microferrioxamines A (11), B (12) and C (13) are linear aliphatic siderophores containing acyl chains of varying lengths45 (Extended Data Fig. 7).

In addition, we observed one molecule with a diagnostic ferrioxamine labeling pattern and iron adduct that had no match in existing natural products databases (Fig. 4c). This unidentified molecule possessed an [M+H]+ adduct at m/z 575.3752 corresponding to the molecular formula C26H50N6O8 suggesting an analog of 8 containing an additional CH2 subunit. This putative desferrioxamine derivative

**Fig. 5 | Comparison of lobosamide structures and biosynthesis.** a, Comparison of the 1H NMR spectra and SIL incorporation in of lobosamides C (15), A (16) and D (17). b, Key correlation spectroscopy (COSY) and heteronuclear multiple bond correlation (HMBC) signals for 17. c, Key rotating frame nuclear Overhauser enhancement spectroscopy (ROESY) correlations for 17. d, Biosynthetic scheme for post-PKS tailoring reactions transforming 15 to 17. DMSO, dimethylsulfoxide.
(14) showed related labeling to 8, with a nearly identical labeling pattern in the [1-15N]glutamate condition, but decreased labeling by [1-13C]acetate, and increased labeling by [1-13C]propionate (Extended Data Fig. 8a). Detailed examination of the fragmentation data revealed that the terminal acetate subunit in 8 was replaced by a propionate unit in 14 (Extended Data Fig. 8). Together, these results show that this strain can produce a large suite of desferrioxamine derivatives, and that these ions can be easily grouped together by relating SIL patterns detected using the IsoAnalyst platform. In total, we identified seven compounds produced by the desferrioxamine BGC, including the unusual desferrioxamine analog microferrioxamine E (14).

**Discovery of lobosamide D using IsoAnalyst.** The second major class of labeled molecules in this dataset had closely related labeling patterns in the [1-13C]acetate, [1-15N]propionate and [1-15N]glutamate conditions (Fig. 4b). Comparison of these labeling patterns (8× [1-13C]acetate, 3× [1-15C]propionate, 1× [1-15N]glutamate) to the annotated BGC list identified two BGCs with an appropriate combination of biosynthetic modules: clusters 30a and 30c (Supplementary Table 2). Both BGCs include a single [1-15N]glutamate incorporation, with BGCs 30a and 30c incorporating five and three [1-15C]propionate units, respectively. Based on these data alone, the molecules could derive from either BGC 30a or 30c. However, strong and consistent incorporation of a minimum of eight acetate units in the molecules of this class thus prioritizes BGC 30c as the cluster responsible for the production of this compound family. This prediction is further strengthened by the observation that the predicted direct incorporation for BGC 30c (8× [1-13C]acetate, 3× [1-15C]propionate, 1× [1-15N]glutamate) exactly matches the observed SIL patterns in the compound family (Supplementary Table 2 and Fig. 4b).

BGC 30c has previously been associated with the production of the lobosamide family of natural products. All the major compounds in this labeled group displayed diagnostic m/z features and distinctive [M+H-H₂O]⁺ in-source fragments consistent with the lobosamide family. The presence of lobosamide C (15) was confirmed by high-performance liquid chromatography (HPLC) purification and NMR comparison (Supplementary Figs. 20–22), whereas lobosamide A (16) was identified in the extracts by UPLC–MS comparison with an authentic standard (Supplementary Fig. 23). Known lobosamide structures only accounted for 6 of the 53 MS features with related SIL patterns. Most of the remaining features were produced in low titer and had mass differences related to the degree of unsaturation and varying oxidations of the known lobosamide scaffold, which suggested a suite of lobosamide analogs.

We isolated a representative molecule from this class with an [M+H]⁺ MS feature at 500.3012 and a calculated molecular formula of C₃₉H₄₅NO₆. Surprisingly, the H NMR spectrum bore low similarity to the H spectra for the known lobosamides (Fig. 5a), although the new compound did share the distinctive in-source dehydration adducts (Extended Data Fig. 9). No additional structurally informative MS/MS fragmentation was observed for any of the lobosamides, limiting the utility of MS/MS spectral matching for compound family assignment. Using a combination of 1D and 2D NMR experiments (Supplementary Figs. 25–35), we determined the planar structure of this new metabolite (Methods, Fig. 5b,c) as a 5–5–6 fused ring system variant of 16 which we named lobosamide D (17). The full absolute configuration of this new molecule was determined using a combination of extensive one-dimensional selective and two-dimensional rotating from nuclear Overhauser spectroscopy experiments, coupled with configurational assignments based on sequence data for selected keto-reductase domains (Supplementary Figs. 31–35).

The proposed biosynthesis of this new member of the lobosamide family via epoxidation followed by intramolecular cyclization (Fig. 5d) is analogous to the production of dracolactams A and B from a common macrolactam precursor and the production of mirilactams C–E from the macrocyclic precursor mirilactam A. The discovery of lobosamide D and determination of the labeling patterns for lobosamides A and C both lend additional evidence to support the connection between this compound class and BGC 30a. Importantly, therefore, IsoAnalyst is able to identify biogenetic relationships between molecules even for those that appear more distantly related based on spectral features, highlighting a key advantage of this new platform for identifying novel chemical variants within the complex molecular phenotypes of BGCs.

**Discussion**

Connecting metabolites to their cognate BGCs has long been a challenge for the field of natural products science. It is difficult or impossible to predict the precise structure(s) produced by most BGCs, which is further complicated by the fact that most BGCs produce a series of related molecules. Similarly, it can be challenging to determine which peaks in untargeted MS metabolomics experiments derive from specialized metabolism, and which of these peaks are biosynthetically related. Using generalist precursors that are incorporated into a wide range of BGC substrates, the IsoAnalyst platform makes it straightforward to highlight major components in the chromatogram that derive from specialized metabolism. For example, in the analysis of the *Micromonospora* sp. we observed 1,444 MS peaks with intensities greater than 1 × 10⁴, of which just 246 had detectable labeling in at least two conditions. Among these, 51 had labeling patterns consistent with the lobosamide BGC. Relationships between SIL patterns therefore allow users to group metabolites into compound families and to identify adducts and in-source fragments from the same molecule, further simplifying the description of the specialized metabolome.

IsoAnalyst prioritizes discovery on the basis of biosynthetic relatedness rather than MS/MS profiling or bioactivities, both of which can provide complementary information but may also vary substantially across families of biosynthetically related compounds. For example, the lobosamide family shares distinctive in-source dehydration adducts, but these signals are not effective for structural characterization by MS/MS due to limited additional fragmentation. Lobosamide D was quickly and definitively associated with other lobosamide compounds on the basis of SIL incorporation, whereas chemical characterization data such as MS fragmentation and NMR provided only ambiguous evidence for the association of this family of compounds. This illustrates how IsoAnalyst is a powerful approach for characterizing complex chemical phenotypes and discovering novel chemical variants produced by both known and unknown BGCs.

A number of challenges remain that preclude the universal detection of all specialized metabolites in a given culture. The ability to detect and map compounds to BGCs is governed by both BGC annotation and precursor selection. The BGC substrate analyses of the organisms used in this study indicate that non-ribosomal peptide-synthetase (NRPS) and polyketide-synthase (PKS) BGCs are most well suited to discovery using this approach. There are several reasons for this bias. BGC identification and annotation tends to be most reliable for these two well-studied biosynthetic classes. Future improvements in BGC informatics, particularly in the area of substrate prediction for less well-studied BGC classes, will increase the coverage of the IsoAnalyst method. Likewise, SIL precursor selection has an important impact on BGC class coverage. For example, terpenes will only have robust SIL incorporation with [1-13C]acetate if the organism possesses the mevalonate pathway. Inclusion of [13C]-labeled isopentenyl pyrophosphate (IPP) as an additional SIL precursor would substantially improve coverage of compounds in this class. Similarly, chorismate-derived precursors are also common, and [13C]-labeled chorismate or shikimate could
help to prioritize specific BGC products containing these substrates. Additional SIL precursors could be included to provide labeling for specific biosynthetic classes. Future advancements in BGC annotation and SIL precursor availability offer the potential for large-scale assessment of the biosynthetic capacity of bacterial strain libraries. In summary, IsoAnalyst provides a novel and flexible approach to quickly define the overall specialized metabolome of a given bacterial culture on the basis of biosynthetic relatedness, meeting a growing need prompted by large-scale genome mining.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41589-021-00949-6.

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Methods

General methods. Stable isotopically labeled compounds were purchased from Cambridge Isotope Laboratories, Inc. The corresponding unlabeled compounds were purchased from ThermoFisher Scientific. All solvents used for UPLC and HPLC were from Optima. Milli-Q water used for chromatography was prepared using a Milli-Q water purification system. High-resolution MS for pure compounds and metabolomics experiments were performed on a Waters Synapt G2S qTOF system. NMR spectra were acquired on a Bruker AVANCE III 600 MHz spectrometer, with a 5 mm TCI cryoprobe, and referenced to residual solvent proton and carbon signals. UV spectra were obtained on an Agilent Cary 300 spectrophotometer. Optical rotations were measured on a Perkin Elmer 341 polarimeter.

Bacterial strains. *Saccharopolyspora erythraea* ATCC 11635 (NRRL 2338) was purchased from the American Type Culture Collection. *Micromonospora* sp. RL09-050-HVF-A was isolated and sequenced as described in Schulze et al.50. In short, *Micromonospora* sp. was cultivated and pelleted from 50 ml of minimal media. The cells were then resuspended in 2 ml of Optima methanol and pellets were collected from a 50 ml culture by centrifugation. DNA was extracted using the Zymo Research ZR Fungal/Bacterial MiniPrep Kit and the Qiagen Genomic Tip 100/G DNA Extraction Kit. DNA was then sequenced at the Institute of Genome Science sequencing facility (IGS, University of Maryland, Baltimore, USA) using a Pacific Bioscience Sequencing machine and a 10 kb insert library. The genome was assembled using the PacBio Hierarchical Genome Assembly Process (HGAP v.07, 2014). The *Micromonospora* sp. RL09-050-HVF-A genome was uploaded to NCBI under the accession number JAGKQP000000000 and the BioProject ID PRX178589.

Parallel well plate fermentation and SIL incorporation. A minimal growth medium was used for all SIL fermentation experiments (10 g starch, 3.4 g sodium glutamate, 0.4 g KH2PO4, 1.2 g K2HPO4, 1.0 g MgSO4·7H2O, 2.0 g NaCl, 1.0 g CaCO3, 0.01 g FeSO4·7H2O, 1.5 mg CuSO4·5H2O, 3.0 mg ZnSO4·7H2O, 1.5 mg CoSO4·7H2O, 1.5 mg MnSO4·H2O and 1.0 mg NaMoO4·2H2O per liter of water). This medium was used for all SIL precursor conditions, except for the [1-15N]glutamate and the corresponding unlabeled glutamate control. For these conditions the same minimal medium was prepared with 50% of the standard amount of sodium glutamate (1.7 g l⁻¹ instead of 3.4 g l⁻¹), and the optimal concentration for each of our SIL precursors, we performed an experiment using *S. erythraea* as described above, in which we added the SIL precursors 30 mM [1-13C]acetate, 30 mM [1-13C]propionate, 5 mM [methyl-13C]methionine and 10 mM [1-15N]glutamate, and unlabeled control precursors at identical concentrations, to different bacterial cultures at 0, 24, 48 and 96 h following inoculation. All cultures were extracted and analyzed after 5 days. *Erythromycin A* (1) was used as a test case to determine the optimal concentrations of each SIL precursor (Supplementary Fig. 1).

To determine the optimal time point for SIL addition, we performed an experiment using *S. erythraea* as described above, in which we added the SIL precursors 30 mM [1-13C]acetate, 30 mM [1-13C]propionate, 5 mM [methyl-13C]methionine and 10 mM [1-15N]glutamate, and unlabeled control precursors at identical concentrations, to different bacterial cultures at 0, 24, 48 and 96 h following inoculation. All cultures were extracted and analyzed after 5 days. *Erythromycin A* (1) was used as a test case to determine the optimal time point for the addition of each SIL precursor (Supplementary Fig. 2). It is important to note that all experiments in this study used the same minimal medium. For experiments using different organisms or base media, precursor concentration and timing of addition should be optimized as described above.

MS data acquisition. Following fermentation, biological samples were diluted with an equal volume of methanol and the supernatants were subjected to chromatography, validation analysis. Chromatographic peaks were acquired on a Waters I-F Class Acquity UPLC system (Acquity HSS T3 1.8 mm, 2 x 100 mm) using a linear gradient (solvent A: H2O + 0.01% formic acid; solvent B: acetonitrile + 0.01% formic acid) of 5–98% B over 5.8 min, a hold at 98% B for 0.3 min followed by a 1.8-min re-equilibration at 5% B. All mass spectra were acquired using a Waters Synapt G2S qTOF running Masslynx v.4.1 SCNN94. MS data were acquired in both a data-independent acquisition mode. The MS detector range was set to 50–1500 m/z in positive mode, with a capillary voltage of 3.5 kV, and a desolvation temperature of 200°C. IsoAnalyst currently only analyzes MS₁ spectra. MS₂ spectra may be acquired simultaneously in a data-independent acquisition experiment or a data-dependent acquisition experiment to assist in further interpretation of the labeling patterns, however IsoAnalyst does not process MS₃ spectra for SIL detection. IsoAnalyst calculates isotopologue ratios using a scan-by-scan comparison of centroided isotopologue peaks, and therefore requires a relatively high scan rate across the chromatographic peak shape for reliable results. We used a 0.2-s scan rate with alternating MS₁ and MS₂ scans, resulting in an overall MS scan rate of 0.4 s. We recommend the use of a similar MS scan rate for data processed in IsoAnalyst to ensure adequate MS coverage across chromatographic peaks for each analyte. In particular, it is important that the number of data-dependent acquisition scans per MS₁ scan be kept low (suggested maximum is three) to prevent large delays between MS scans that can negatively impact data coverage for small peaks in the chromatogram.

Standard peak processing to generate input files for IsoAnalyst. The two types of MS data files that are required as input for IsoAnalyst are centroided scan-by-scan MS peak lists for all samples and deisotoped mz files and retention time feature lists for the unlabeled control samples only (Extended Data Fig. 2a). These files can be generated for IsoAnalyst by processing all MS data, and deisotoped feature lists. The file importer is configured to accept feature lists from the popular open-source MS processing platform MZmine2 by default. Feature lists from other processing software must be reformatted to match this column layout. Scan-by-scan mz files can be generated by converting original raw mass spectrometer files to .mzML using the open-source tool MSConvert. Details about both file formats and example files are available in the README.md file in the GitHub repository. The first step of the IsoAnalyst workflow aligns the unlabeled control sample feature lists by mass and retention time to generate a ground truth list of all features detected across the unlabeled conditions. Alternatively, users may perform feature alignment by other methods and submit a ground truth feature list in the second step of IsoAnalyst, with the centroided .mzML files for all samples (Extended Data Fig. 2a).

The aligned feature lists are used to determine the monoisotopic mass (M₀) and retention time range for each feature in the downstream processing steps. It is important, therefore, that settings used for feature detection include a deisotoping step to ensure that all features included are identified only by the M₀ mass to prevent redundancy. More information about file input requirements can be found on GitHub (https://github.com/liningtonlab/isoolanalysis).

Interrogation of SIL experimental data for complete isotopologue information. Because isotopic distribution patterns vary significantly between analytes, we found that existing MS analysis software could not correctly identify the M₀ peak of experimentally labeled features in the unlabeled conditions. Instead, we used the M₀ mass of each MS feature from the ground truth list as an anchor point to interrogate the labeled MS data for relevant isotopologue distribution patterns. This was accomplished using a custom data processing script that interrogated the scan-by-scan deisotoped centroided MS data from each experimental condition for the presence of each concentrations of each SIL: 100, 10, and 0.1 mM [1-13C]acetate, 100, 10, and 0.1 mM [1-13C]propionate, 16.5, 10, and 0.1 mM [methyl-13C]methionine, and 20, 10 and 2 mM [1-15N]glutamate. In all conditions, the total concentration of glutamate is 20 mM, because glutamate is the only nitrogen source in the minimal media. For the [1-15N]glutamate labeling condition, we tested three ratios of [1-15N]glutamate and unlabeled glutamate, so that the total available nitrogen was the same in every condition. Unlabeled controls were performed as four replicates with matching concentrations of unlabeled acetate, propionate, methionine and glutamate, respectively. Erythromycin A (1) was used as a test case to determine the optimal concentrations of each SIL precursor (Supplementary Fig. 1).
isotopologue peak (M0, M1, M2 and so on) for every feature in the ground truth list (Extended Data Fig. 2b). Because the m/z value for the M0 of each feature is provided in the ground truth list, this approach can identify all isotopologues that are present in the SIL experiment. However, the analysis has no power to determine the type and number of substrates needed to biosynthesize the product. In some cases, such as for NRPPs, our analysis procedure was done with the assumption that no more than one SIL precursor is present in the SIL sample data as it scans for computed m/z values. Isotopologue data are interrogated this way for both unlabeled and labeled control samples. For identifying isotopologues in the unlabeled datasets, and in the SIL conditions containing only 15N enrichment, the mass difference of 1.00335 m/z is used. The resolving power of the system used for this study is not sufficient to differentiate between the natural occurrence of 15N and the enrichment of 13N, therefore in the [1-15]N glutamate condition, the mass isozotope peaks M1, M2 and so on represent a mixture of isotopologues containing either 15N, 13C or some glutamate condition. The contribution of naturally occurring 13C to the isotopologue peaks as ‘isotopologues’, however we use the mass difference between 14N and 15N (0.99704 m/z) to compute the theoretical SIL isotopologue peaks in all 13C enrichment condition. The contribution of naturally occurring 13C to the isotopologue distribution in the SIL samples is accounted for in the next step, where isotopologue ratios are compared directly between labeled and unlabeled conditions.

Determination of SIL incorporation into MS features. To determine if an MS feature is isotopically enriched by a given precursor, the IsoAnalyzer algorithm first determines the intensity ratio for the M1 (first isotopologue) versus M0 (monoisotopic mass) peaks for that feature in the unlabeled control condition by plotting the intensity values for M1 and M0 in each scan (Extended Data Fig. 3). Because the natural abundance of 13C, the M1:M0 ratio of a compound in the unlabeled condition can be calculated based on the molecular formula and vice versa. Molecular formula prediction for untargeted MS metabolomics data to assist in compound identification is common; however, it is computationally time-consuming to predict molecular formulas for thousands of features, when many of them will not have detectable SIL precursor incorporation. We opted to look directly at the natural M1:M0 ratio for each feature in the unlabeled condition, rather than predicting the molecular formula for every analyte to determine the expected M1:M0 relationship. Because all SIL precursors used in this study are singly labeled, incorporation of 13C for that feature will not increase the M1:M0 intensity ratio for that condition. The M1:M0 ratio of each feature in the SIL data is then compared with the natural M1:M0 ratio for the same feature in the unlabeled samples using a two-tailed Welch’s t test, with a P value cut-off of 0.05 (Fig. 2c,d). Although we perform a two-tailed t test in this analysis, we only determine an isotopologue peak to be enriched in an SIL precursor if the M1:m0 ratio is significantly greater than the natural M1:M0 ratio. This is effectively a one-tailed t test (P value cut-off of 0.025), where we use a combination of the two-tailed P value (< 0.05) and the test statistic (t < 0) to decide if a isotopologue is enriched with an SIL precursor (Fig. 2d). If the initial t test is insignificant, the MS feature is determined to have no isotopic enrichment; if, however, the initial t test is significant, the feature is annotated as a putative SIL precursor condition. When a feature is assigned as isotopically enriched with a given precursor, IsoAnalyzer iteratively compares the intensity ratios for subsequent isotopologue pairs (for example, M2:M1, M3:M2 and so on) until the isotopologue ratio is no longer statistically distinguishable from the natural M1:M0 ratio. At this point, isotopic enrichment can no longer be confidently assigned beyond that position (Fig. 2d). This analysis therefore assigns a minimum degree of isotopic labeling for a given precursor. A brief discussion summarizing why this statistical approach was used over other available analytical platforms for analyzing SIL MS metabonomics data can be found in Supplementary Note 1.

We use four replicates for the unlabeled control and four replicates for each SIL tracer condition in our experiment. However, a statistical analysis using a minimum of only three replicates for each isotopologue ratio in the Welch’s t test to accommodate situations in which a given feature is not detected in one of the replicates, or is not detected in at least five scans for the linear regression analysis. Supplementary Table 4 shows the power analysis for the data table shown in Fig. 2d using the TestIndPower function from the smatstmodels library in Python. This analysis is performed on data from just three replicates (owing to a technical problem with data acquisition for the fourth replicate for the labeled version of this sample) and was selected to evaluate the method with minimal replicates in the experimental condition.

All of the isotopologue ratios that have statistically significant P values in Supplementary Table 4 have power analysis. The only isotopologue ratio that was not significant (M5:M4, P = 0.14) had a power value of 0.52 indicating that these groups cannot be differentiated by a sample size of N = 3. Very small differences that are within the standard deviation of the mean values being compared are not detectable using this sample size, such as the M5:M4 ratio (Supplementary Table 4). However, because the standard deviations are overall very low in these measurements, relatively small differences can still be statistically detected, such as in the M4:M3 and M6:M5 ratios (Supplementary Table 4). Therefore, even in situations in which a feature is only observed in three replicates, the analysis has sufficient power to support the determination of maximum labeled isotopologue values.

IsoAnalyzer evaluates every MS feature in the ground truth list in each labeling condition to determine both whether the feature is isotopically enriched in that condition, and how many positions can confidently be assigned as labeled. These data create a profile for each MS feature indicating the number of labeled SIL precursor tested (Fig. 2c). The final step is to combine the labeling information into a summary file with every feature from the ground truth list and the number of SIL precursors detected in each condition (Extended Data Fig. 2b).

Bioanalytical gene cluster substrate annotation. The genomes of S. erythraea NRRL B3388 and the Micromonospora sp. isolate were first mined for BGCs using antiSMASH-DB (entry generated with antiSMASH 5.2) and antiSMASH web server v6.0.0, respectively, resulting in the discovery of 36 BGCs for S. erythraea and 26 BGCs for the Micromonospora strain. Predicted BGCs were used to list the type and number of substrates needed to biosynthesize the product. In some cases, such as for NRPPs, our analysis procedure was done with the assumption that no more than one SIL precursor is present in the SIL sample data as it scans for computed m/z values. IsoAnalyst evaluates every MS feature in the ground truth list in each labeling condition to determine both whether the feature is isotopically enriched in that condition, and how many positions can confidently be assigned as labeled. These data create a profile for each MS feature indicating the number of labeled SIL precursor tested (Fig. 2c). The final step is to combine the labeling information into a summary file with every feature from the ground truth list and the number of SIL precursors detected in each condition (Extended Data Fig. 2b).

Large-scale fermentation, extraction and fractionation of S. erythraea and Micromonospora sp. S. erythraea and Micromonospora sp. were each grown in 2.8-l Fernbach flasks containing 20.0 g of Amberlite XAD-16 adsorbent resin, a stainless-steel spring, and 11 of the minimal media as described above for use in the SIL experiment. All large-scale fermentations were done without the supplementation of SIL precursors. Cultures were shaken at 200 r.p.m. for 6 days, at which time the cultures were filtered by vacuum filtration on Whatman glass microfiber filters. The cells and resin were collected and extracted with 250 ml of 1:1 methanol/dichloromethane. The organic extract was collected by vacuum filtration and dried by rotary evaporation. The crude organic extract was initially separated into seven fractions by stepwise methanol/water elution (10, 20, 40, 60, 80 and 100 v/v) and an additional ethyl acetate wash step on a RediSep Rf C18 cartridge (Teledyne Isco) using a Teledyne Isco CombiFlash RF flash chromatography system.

Isolation of compounds 2 and 3. Purification of compounds 2 and 3 was performed on a Waters Acquity UPLC system with a Waters Acquity UPLC quaternary pump (Waters Atlantis T3 prep OBO column 5 μm, 25 x 250 mm) using an elution gradient of 45–83% B over 21 min, at a flow rate of 20 ml/min. Erythronolide B (2) was collected at 6.5 min by mass detection for the ion m/z 425.4 and 3 was collected at 9.5 min by mass detection for the ion m/z 529.4. MEB (3) was further purified using an isocratic separation of 42% B, with MEB eluting from the column at 11.8 min. In total, 2.5 mg of 2 and 4.5 mg of 3 were isolated and analyzed by NMR for comparison with authentic standards (Supplementary Figures S3–S12).

Isolation of compounds 15 and 17. Purification of 15 and 17 was carried out using an Agilent 1200 series HPLC system. Lobosamide C (15) (0.7 mg) was isolated from the 100% methanol fraction by HPLC (Phenomenex Kinetex XB-C18 5 μm, 250 mm x 4.6 mm) using an isocratic separation (45% methanol + 0.02% formic acid, 45% H2O + 0.02% formic acid, and 10% isopropyl alcohol with 0.02% formic acid) with a flow rate of 1.2 ml/min for 20 min. Lobosamide C (15) was eluted from the column at 34.4 min and was collected by UV detection at 300 nm. Lobosamide C (17) (0.4 mg) was isolated from the 40% methanol fraction by HPLC (Phenomenex Kinetex XB-C18 5 μm, 250 mm x 4.6 mm) using an isocratic separation (23% acetonitrile + 0.02% formic acid and 77% H2O + 0.02% formic acid) with a flow rate of 1.2 ml/min for 20 min. Lobosamide C (17) was eluted from the column at 15.0 min and was collected by UV detection at 280 nm.
C₃₀H₄₁NO₆, 500.3007; found, 500.3012 (see Supplementary Table 3 for NMR shifts). SMILES: C=C(C[C@H]1C[C@@H](O)[C@H=O][C@H=O][C@H=O][C@H=O][C=O]C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/C=C/...
Extended Data Fig. 1 | TCA cycle labeling by [1-13C]acetate. Red filled circles represent 13C derived from [1-13C]acetate following its direct transformation to acetyl-CoA. When a 13C labeled succinyl-CoA is converted to succinate, the position of the 13C label becomes ambiguous due to the symmetry of succinate, represented by open red circles, indicating that either position has an equal chance of being labeled. Labeled oxaloacetate re-enters the TCA cycle resulting in up to two 13C incorporation events in citrate, isocitrate, and α-ketoglutarate. Groups of amino acids that are derived from TCA cycle biosynthetic precursors are indicated. The interconversion of succinate and succinyl-CoA leads to the indirect incorporation of 13C into the C1 position of methylmalonyl-CoA as indicated by an open red circle while the direct labeling of the C4 position of methylmalonyl-CoA is lost to decarboxylation during the PKS condensation of methylmalonyl-CoA units.
Extended Data Fig. 2 | IsoAnalyst MS data processing workflow. (a) Required data pre-processing steps to generate input files for IsoAnalyst. Files (indicated as parallelograms) highlighted with a light gray box are required input files generated by third party tools that can perform the processes shown in dashed rectangles. We recommend MSconvert and MZmine for these processes however other programs may be used as long as the .csv input meets the requirements described in the software documentation available in the GitHub repository. The ground truth feature list of features aligned across samples is highlighted in a dark gray box and may be generated by the 'Prep' step of the IsoAnalyst program (highlighted in green) or by third party tools (for example, MZmine). (b) IsoAnalyst performs the following steps: all isotopologue peak information for every feature is first scraped from the .mzML data files in the 'Scrape' step (highlighted in blue). In the 'Analyze' step (highlighted in orange), the isotopologue ratios are compared for every feature in each SIL condition to determine the extent of labeling. Finally, a summary file is generated containing all of the SIL incorporation profiles for every feature that contains labeling in two or more conditions.
Extended Data Fig. 3 | MS Data centroiding and isotopologue ratio plotting. (a) Diagram of LC-MS data acquisition showing mass spectra collected at regular time intervals across a chromatographic peak. Each orange line represents a single mass spectrum, or scan, containing $m/z$ vs. intensity values across the instrument’s range. Data are first centroided, or peak picked, to give a single data point corresponding to the intensity of every $m/z$ value in a scan. (b) All centroided scan data for a given feature plotted together as single points. (c) All centroided scan data for the first two isotopologue peaks, M1 and M0, plotted by matching scans. The slope of the linear trend line in (c) is the isotopologue ratio used in the analysis step of the IsoAnalyst workflow.
Extended Data Fig. 4 | SIL incorporation for erythrochelin (7). (a) Substrates used in the biosynthesis of 7, and both the expected and observed labeling of 7. (b) Structures and mass spectra for the iron adduct (m/z 657.2064) and the protonated adduct (m/z 604.2950) of 7 in the [1-13C]acetate and [1-15N]glutamate conditions. [1-13C]Propionate and [methyl-13C]methionine conditions are not shown as 7 was not produced under the [1-13C]propionate condition and no SIL incorporation occurred under the [methyl-13C]methionine condition.
Extended Data Fig. 5 | SIL incorporation in fragments of 7. Mass spectra of fragments m/z 390.1990 (a), m/z 303.1666 (b), m/z 173.0932 (c) and m/z 131.0827 (d) under [1-13C]acetate and [1-15N]glutamate conditions indicate that the detected SIL incorporation is within the expected labeling maximums for the biosynthetic subunits derived from ornithine and acetyl-CoA.
Extended Data Fig. 6 | IsoAnalyst profiles for desferrioxamine analogues. (a) Diagram showing all labeled MS features detected in the metabolome of Micromonospora sp. Circles represent features with IsoAnalyst profiles resembling the desferrioxamines. Diamonds represent features with IsoAnalyst profiles resembling the lobosamides. (b) Structures and IsoAnalyst profiles for desferrioxamine compounds indicated by filled gray circles in (a).
Extended Data Fig. 7 | Iso Analyst profiles of microferrioxamines and their fragments. Each box contained the expected and observed SIL incorporation for various ions associated with compounds 11, 12, and 13. Due to the substrate flexibility of the acyl transferase DesC\(^{19}\), the exact number of acetate-derived subunits cannot be accurately predicted.
Extended Data Fig. 8 | IsoAnalyst profiles of desferroxamines and their fragments. (a) Structures with observed fragmentation indicated and mass spectra for [M+H]⁺ ions of 8 and 14. Expected (Exp.) and observed (Obs.) labeling for 8 and 14 in each condition is indicated in boxes. (b) Mass spectra of observed b-ion and y-ion fragments for 8 and 14. Expected and observed labeling for fragments indicated in boxes.
Extended Data Fig. 9 | Lobosamide MS adducts. Adducts and in-source fragment ions corresponding to compounds 15, 16, and 17, which had SIL incorporation detected by IsoAnalyst.
Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

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- For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection
- Mass spectrometry data were acquired on a Waters SYNAPT G2Si instrument running MassLynx (v4.1 SCN941).

Data analysis
- Data analysis of mass spectrometry data was performed using custom Python code provided in the GitHub repository [https://github.com/liningtonlab/isoanalyst]. The genomes of S. erythraea NRRL 2338 and the Micromonospora sp. isolate were mined for BGCs using antiSMASH-DB [entry generated with antiSMASH 5.2] and antiSMASH web server v6.0.0 respectively.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:
- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

Whole genome sequence (WGS) data for Micromonospora sp. RL09-050-HVF-A was uploaded to NCBI GenBank under the accession number JAGKQP000000000 and the BioProject ID PRJNA718589. The version described in this paper is version JAGKQP010000000. WGS data for Saccharopolyspora erythraea are available in NCBI with the accession code NC_009142. The processed mass spectrometry data, antiSMASH output for Micromonospora sp. RL09-050-HVF-A, and isoAnalyst output files that support the findings of this study have been deposited in Zenodo [10.5281/zenodo.4711483]. The MIBig database used in this study is available at https://mibig.secondarymetabolites.org/. Raw mass spectrometry data have been deposited to MassIVE under the accession numbers MSV00008724 (S. erythraea) and MSV00008723 (Micromonospora sp.). The structure of lobosamide D has been deposited to the Natural Products Atlas (www.npatlas.org). The NMR
data for lobosamide D have been deposited to the Natural Products Magnetic Resonance Database (NP-MRD; www.np-mrd.org) under accession number NP00344012. MS/MS spectra for lobosamides C and D have been deposited to the Global Natural Products Social molecular networking database (GNPS; https://gnps.ucsd.edu) under accession numbers CCMSLIB000006685341 and CCMSLIB000006709936 respectively.

Field-specific reporting

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Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

| Sample size | The sample size in this study is determined by replicate samples analyzed by UPLC-MS. We use four technical replicates to calculate the isotopologue ratios which are used in the statistical analysis (t-test) in this study. Supplementary Table 5 contains power analysis results which indicate that three replicates provide 100% power in statistically significant cases. Instrument and sample variation sometimes lead to a loss of sample data, resulting in only three replicates. Iso Analyst requires a minimum of three replicate samples in order to consider an isotopologue ratio for analysis.
|---|---|---|
| Data exclusions | Mass spectrometry data were filtered to remove signals that eluted in the column wash and re-equilibration step (after 5.8 minutes on the chromatogram). This filtration was predetermined and is common practice in mass spectrometry metabolomics studies because the column wash is used exclusively for final column cleaning and does not contain usable chromatographic information.
| Replication | Each labeling condition was cultured and analyzed as four independent replicates. All replicates derived from the same initial seed culture in all cases. All replicate attempts were successful with the exception of one replicate in one labeling condition for one organism (1-13C-acetate labeling for S. erythraea).
| Randomization | The LCMS sample worklist was randomized for MS data acquisition to eliminate systematic carryover of analytes between samples. No further randomization was applied during the experiment because subsequent analytical steps involved extraction of labeling values from labeled and unlabeled MS data based on labeled precursor and results were independent of order of analysis.
| Blinding | Blinding was not relevant to this study because raw data were acquired in a single analytical run using an autosampler and a randomized worklist, and were processed by the automated data analysis pipeline without investigator intervention, precluding bias in data analysis. Data interpretation does require investigator input, but involves alignment of results files from BGC and metabolomics data analysis outputs that contain integer predictions of feedstock incorporation, meaning that the interpretation is also rule-based.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

| n/a | Involved in the study |
|---|---|---|
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| ☒ Eukaryotic cell lines |
| ☒ Palaeontology and archaeology |
| ☒ Animals and other organisms |
| ☒ Human research participants |
| ☒ Clinical data |
| ☒ Dual use research of concern |

Methods

| n/a | Involved in the study |
|---|---|---|
| ☐ ChIP-seq |
| ☐ Flow cytometry |
| ☐ MRI-based neuroimaging |