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# A standardised ecosystem services framework for the deep sea

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Appendix 1. For our second review, a total of 182 papers were considered relevant for this study's analysis. References are alphabetically listed according to service type.

#	Ecosystem Services	Reference
1	Nutrient cycling	Bart, M. C. <i>et al.</i> (2021) 'Dissolved organic carbon (DOC) is essential to balance the metabolic demands of four dominant North-Atlantic deep-sea sponges', pp. 925–938. doi: 10.1002/lno.11652.
1	Nutrient cycling	Corinaldesi, C. (2015) 'New perspectives in benthic deep-sea microbial ecology', <i>Frontiers in Marine Science</i> , 2(MAR), pp. 1–12. doi: 10.3389/fmars.2015.00017.
1	Nutrient cycling	Danovaro, R., Snelgrove, P. V. R. and Tyler, P. (2014) 'Challenging the paradigms of deep-sea ecology', <i>Trends in Ecology &amp; Evolution</i> , 29(8), pp. 465–475. doi: <a href="https://doi.org/10.1016/j.tree.2014.06.002">https://doi.org/10.1016/j.tree.2014.06.002</a> .
1	Nutrient cycling	Dell'Anno, A., Corinaldesi, C. and Danovaro, R. (2015) 'Virus decomposition provides an important contribution to benthic deep-sea ecosystem functioning', pp. E2014–E2019. doi: 10.1073/pnas.1422234112.
1	Nutrient cycling	Dell'Anno, A. <i>et al.</i> (2013) 'Trophic state of benthic deep-sea ecosystems from two different continental margins off Iberia', <i>BIOGEOSCIENCES</i> , 10(5), pp. 2945–2957. doi: 10.5194/bg-10-2945-2013.
1	Nutrient cycling	Dombrowski, N. <i>et al.</i> (2017) 'Genomic insights into potential interdependencies in microbial hydrocarbon and nutrient cycling in hydrothermal sediments', p. 106. doi: 10.1186/s40168-017-0322-2.
1	Nutrient cycling	Dunham, A. <i>et al.</i> (2018) 'Assessing condition and ecological role of deep-water biogenic habitats: Glass sponge reefs in the Salish Sea', pp. 88–99. doi: 10.1016/j.marenvres.2018.08.002.
1	Nutrient cycling	Dunlop, K. M. <i>et al.</i> (2016) 'Carbon cycling in the deep eastern North Pacific benthic food web: Investigating the effect of organic carbon input', <i>LIMNOLOGY AND OCEANOGRAPHY</i> , 61(6), pp. 1956–1968. doi: 10.1002/lno.10345.
1	Nutrient cycling	Gooday, A. J. <i>et al.</i> (2020) 'Protist diversity and function in the dark ocean – Challenging the paradigms of deep-sea ecology with special emphasis on foraminiferans and naked protists', <i>European Journal of Protistology</i> , 75, p. 125721. doi: <a href="https://doi.org/10.1016/j.ejop.2020.125721">https://doi.org/10.1016/j.ejop.2020.125721</a> .
1	Nutrient cycling	Huang, J.-M. <i>et al.</i> (2019) 'New microbial lineages capable of carbon fixation and nutrient cycling in deepsea sediments of the northern South China Sea'. doi: 10.1128/AEM.00523-19.
1	Nutrient cycling	Langlet, D. <i>et al.</i> (2020) 'Foraminiferal Ecology and Role in Nitrogen Benthic Cycle in the Hypoxic Southeastern Bering Sea', <i>FRONTIERS IN MARINE SCIENCE</i> , 7. doi: 10.3389/fmars.2020.582818.
1	Nutrient cycling	Li, Y. <i>et al.</i> (2018) 'Metagenomic insights into the microbial community and nutrient cycling in the western subarctic Pacific Ocean'. doi: 10.3389/fmicb.2018.00623.
1	Nutrient cycling	Li, Z. <i>et al.</i> (2016) 'Metagenomic Analysis of Genes Encoding Nutrient Cycling Pathways in the Microbiota of Deep-Sea and Shallow-Water Sponges', <i>Marine Biotechnology</i> , 18(6), pp. 659–671. doi: 10.1007/s10126-016-9725-5.
1	Nutrient cycling	Lin, G. <i>et al.</i> (2021) 'Geochemical and microbial insights into vertical distributions of genetic potential of N-cycling processes in deep-sea sediments', <i>Ecological Indicators</i> , 125, p. 107461. doi: <a href="https://doi.org/10.1016/j.ecolind.2021.107461">https://doi.org/10.1016/j.ecolind.2021.107461</a> .

1	Nutrient cycling	Maldonado, M. <i>et al.</i> (2021) ‘A Microbial Nitrogen Engine Modulated by Bacteriosyncytia in Hexactinellid Sponges: Ecological Implications for Deep-Sea Communities’. doi: 10.3389/fmars.2021.638505.
1	Nutrient cycling	Román, S. <i>et al.</i> (2019) ‘Microbial community structure and functionality in the deep sea floor: Evaluating the causes of spatial heterogeneity in a submarine canyon system (NW Mediterranean, Spain)’. doi: 10.3389/fmars.2019.00108.
1	Nutrient cycling	Rooks, C. <i>et al.</i> (2020) ‘Deep-sea sponge grounds as nutrient sinks: denitrification is common in boreo-Arctic sponges’, <i>BIOGEOSCIENCES</i> , 17(5), pp. 1231–1245. doi: 10.5194/bg-17-1231-2020.
1	Nutrient cycling	Vilas, D. <i>et al.</i> (2020) ‘Kelp-carbon uptake by Arctic deep-sea food webs plays a noticeable role in maintaining ecosystem structural and functional traits’, <i>Journal of Marine Systems</i> . Elsevier, 203(July 2019), p. 103268. doi: 10.1016/j.jmarsys.2019.103268.
1	Nutrient cycling	Xu, Z. <i>et al.</i> (2017) ‘Live benthic foraminifera in the Yellow Sea and the East China Sea: Vertical distribution, nitrate storage, and potential denitrification’, <i>Marine Ecology Progress Series</i> , 571, pp. 65–81. doi: 10.3354/meps12135.
1	Nutrient cycling	Yamanaka, T. <i>et al.</i> (2015) ‘Re-evaluation of nutrient sources for deep-sea wood-boring bivalves using the isotopic composition of bulk C, N, S, and amino acid nitrogen’, pp. 157–165. doi: 10.3354/meps11510.
1	Nutrient cycling	Zhou, J. <i>et al.</i> (2020) ‘Phosphorus species in deep-sea carbonate deposits: Implications for phosphorus cycling in cold seep environments’, pp. 1–17. doi: 10.3390/min10070645.
2	Chemosynthetic primary production	Campanyà-Llovet, N., Snelgrove, P. V. R. and Parrish, C. C. (2017) ‘Rethinking the importance of food quality in marine benthic food webs’, <i>Progress in Oceanography</i> , 156, pp. 240–251. doi: <a href="https://doi.org/10.1016/j.pocean.2017.07.006">https://doi.org/10.1016/j.pocean.2017.07.006</a> .
2	Chemosynthetic primary production	Grupe, B. M. <i>et al.</i> (2015) ‘Methane seep ecosystem functions and services from a recently discovered southern California seep’, <i>Marine Ecology</i> , 36(S1), pp. 91–108. doi: 10.1111/maec.12243.
2	Chemosynthetic primary production	Levin, L. A. <i>et al.</i> (2016) ‘Hydrothermal vents and methane seeps: Rethinking the sphere of influence’, <i>Frontiers in Marine Science</i> , 3(MAY), pp. 1–23. doi: 10.3389/fmars.2016.00072.
2	Chemosynthetic primary production	McNichol, J. <i>et al.</i> (2018) ‘Primary productivity below the seafloor at deep-sea hot springs’, pp. 6756–6761. doi: 10.1073/pnas.1804351115.
2	Chemosynthetic primary production	Petersen, J. M. (2016) ‘Ecology and Fisheries: Dark Carbon on Your Dinner Plate’, <i>Current Biology</i> , 26(24), pp. R1277–R1279. doi: <a href="https://doi.org/10.1016/j.cub.2016.11.016">https://doi.org/10.1016/j.cub.2016.11.016</a> .
2	Chemosynthetic primary production	Sogin, E. M., Leisch, N. and Dubilier, N. (2020) ‘Chemosynthetic symbioses’, <i>Current Biology</i> , 30(19), pp. R1137–R1142. doi: <a href="https://doi.org/10.1016/j.cub.2020.07.050">https://doi.org/10.1016/j.cub.2020.07.050</a> .
2	Chemosynthetic primary production	Tresa, T.R., Das, A., Ponnappakkam Adikesavan, L.B., 2018. A Review on the Phylogeography of Potentially Chemoautotrophic Bacteria from Major Vent and Seep Fauna and Their Contribution to Primary Production. <a href="https://doi.org/10.1080/01490451.2018.1440035">https://doi.org/10.1080/01490451.2018.1440035</a>
2	Chemosynthetic primary production	Yamanaka, T. <i>et al.</i> (2015) ‘A compilation of the stable isotopic compositions of carbon, nitrogen, and sulfur in soft body parts of animals collected from deep-sea hydrothermal vent and methane seep fields: Variations in energy source and importance of subsurface microbial processes’, pp. 105–129. doi: 10.1007/978-4-431-54865-2_10.

3	Secondary production	Tecchio, S. <i>et al.</i> (2013) ‘Trophic Dynamics of Deep-Sea Megabenthos Are Mediated by Surface Productivity’, <i>PLOS ONE</i> , 8(5). doi: 10.1371/journal.pone.0063796.
3	Secondary production	Vilas, D. <i>et al.</i> (2020) ‘Kelp-carbon uptake by Arctic deep-sea food webs plays a noticeable role in maintaining ecosystem structural and functional traits’. doi: 10.1016/j.jmarsys.2019.103268.
4	Biologically mediated habitat	D’Onghia, G., Sion, L., Capezzuto, F., 2019. Cold-water coral habitats benefit adjacent fisheries along the Apulian margin (central Mediterranean). <a href="https://doi.org/10.1016/j.fishres.2019.01.021">https://doi.org/10.1016/j.fishres.2019.01.021</a>
4	Biologically mediated habitat	Henry, L.A., Navas, J.M., Hennige, S.J., Wicks, L.C., Vad, J., Murray Roberts, J., 2013. Cold-water coral reef habitats benefit recreationally valuable sharks. <i>Biol. Conserv.</i> 161, 67–70. <a href="https://doi.org/10.1016/j.biocon.2013.03.002">https://doi.org/10.1016/j.biocon.2013.03.002</a>
4	Biologically mediated habitat	Kousteni, V., 2021. Shedding light on the deep: The case of the velvet belly lanternshark in the North Aegean Sea. <a href="https://doi.org/10.1111/jfb.14702">https://doi.org/10.1111/jfb.14702</a>
4	Biologically mediated habitat	Turner, P.J., Thaler, A.D., Freitag, A., Collins, P.C., Colman Collins, P., 2019. Deep-sea hydrothermal vent ecosystem principles: Identification of ecosystem processes, services and communication of value. <i>Mar. Policy</i> 101, 118–124. <a href="https://doi.org/https://doi.org/10.1016/j.marpol.2019.01.003">https://doi.org/https://doi.org/10.1016/j.marpol.2019.01.003</a>
5	Medicinal, biochemical and genetic resources	Aevansson, A., Kaczorowska, A.K., Adalsteinsson, B.T., Ahlqvist, J., Al-Karadaghi, S., Altenbuchner, J., Arsin, H., Atlason, U.A., Brandt, D., Cichowicz-Cieslak, M., Cornish, K.A.S., Courtin, J., Dabrowski, S., Dahle, H., Djefane, S., Dorawa, S., Dusaucy, J., Enault, F., Fedoy, A.E., Freitag-Pohl, S., Fridjonsson, O.H., Galiez, C., Glomsaker, E., Guerin, M., Gundeso, S.E., Gudmundsdottir, E.E., Gudmundsson, H., Hakansson, M., Henke, C., Helleux, A., Henriksen, J.R., Hjorleifdottir, S., Hreggvidsson, G.O., Jasilionis, A., Jochheim, A., Jonsdottir, I., Jonsdottir, L.B., Jurczak-Kurek, A., Kaczorowski, T., Kalinowski, J., Kozlowski, L.P., Krupovic, M., Kwiatkowska-Semrau, K., Lanes, O., Lange, J., Lebrat, J., Linares-Pasten, J., Liu, Y., Lorentsen, S.A., Lutterman, T., Mas, T., Merre, W., Mirdita, M., Morzywolek, A., Ndela, E.O., Karlsson, E.N., Olgudottir, E., Pedersen, C., Perler, F., Petursdottir, S.K., Plotka, M., Pohl, E., Prangishvili, D., Ray, J.L., Reynisson, B., Robertsdottir, T., Sandaa, R.A., Sczyrba, A., Skirnisdottir, S., Soding, J., Solstad, T., Steen, I.H., Stefansson, S.K., Steinegger, M., Overa, K.S., Striberny, B., Svensson, A., Szadkowska, M., Tarrant, E.J., Terzian, P., Tourigny, M., van den Bergh, T., Vanhalst, J., Vincent, J., Vroling, B., Walse, B., Wang, L., Watzlawick, H., Welin, M., Werbowy, O., Wons, E., Zhang, R.S., 2021. Going to extremes - a metagenomic journey into the dark matter of life. <i>FEMS Microbiol. Lett.</i> 368. <a href="https://doi.org/10.1093/femsle/fnab067">https://doi.org/10.1093/femsle/fnab067</a>
5	Medicinal, biochemical and genetic resources	Ameen, F., AlNadhari, S., Al-Homaidan, A.A., 2021. Marine microorganisms as an untapped source of bioactive compounds. <i>Saudi J. Biol. Sci.</i> 28, 224–231. <a href="https://doi.org/https://doi.org/10.1016/j.sjbs.2020.09.052">https://doi.org/https://doi.org/10.1016/j.sjbs.2020.09.052</a>
5	Medicinal, biochemical and genetic resources	Back, C.R., Stennett, H.L., Williams, S.E., Wang, L.Y., Gomez, J.O., Abdulle, O.M., Duffy, T., Neal, C., Mantell, J., Jepson, M.A., Hendry, K.R., Powell, D., Stach, J.E.M., Essex-Lopresti, A.E., Willis, C.L., Curnow, P., Race, P.R., 2021. A New Micromonospora Strain with Antibiotic Activity Isolated from the Microbiome of a Mid-Atlantic Deep-Sea Sponge. <i>Mar. Drugs</i> 19. <a href="https://doi.org/10.3390/md19020105">https://doi.org/10.3390/md19020105</a>
5	Medicinal, biochemical and genetic resources	Batista-García, R.A., Sutton, T., Jackson, S.A., Tovar-Herrera, O.E., Balcázar-López, E., Sánchez-Carbente, M.D.R., Sánchez-Reyes, A., Dobson, A.D.W., Folch-Mallol, J.L., 2017. Characterization of lignocellulolytic

activities from fungi isolated from the deep-sea sponge *Stelletta normani*.  
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5	Medicinal, biochemical and genetic resources	Borchert, E., Jackson, S.A., O’Gara, F., Dobson, A.D.W., 2016. Diversity of Natural Product Biosynthetic Genes in the Microbiome of the Deep Sea Sponges <i>Inflatella pellicula</i> , <i>Poecillastra compressa</i> , and <i>Stelletta normani</i> . <i>Front. Microbiol.</i> 7. <a href="https://doi.org/10.3389/fmicb.2010.01027">https://doi.org/10.3389/fmicb.2010.01027</a>
5	Medicinal, biochemical and genetic resources	Cassavaugh, C.M., Lamont, S., Szuch, C.P., Carfagno, A., Gillevet, P.M., Bishop, B.M., Cook, G.M., 2020. Combatting Antibiotic Resistance: Bioprospecting for Antimicrobial Peptides in the Deep-Sea Coral <i>Lophelia pertusa</i> . <i>Integr. Comp. Biol.</i> 60 MA-P, E293–E293.
5	Medicinal, biochemical and genetic resources	Collins, F.W.J., Walsh, C.J., Gomez-Sala, B., Guijarro-García, E., Stokes, D., Jakobsdóttir, K.B., Kristjánsson, K., Burns, F., Cotter, P.D., Rea, M.C., Hill, C., Ross, R.P., 2021. The microbiome of deep-sea fish reveals new microbial species and a sparsity of antibiotic resistance genes. <a href="https://doi.org/10.1080/19490976.2021.1921924">https://doi.org/10.1080/19490976.2021.1921924</a>
5	Medicinal, biochemical and genetic resources	Daletos, G., Ebrahim, W., Ancheeva, E., El-Neketi, M., Song, W., Lin, W., Proksch, P., 2018. Natural products from deep-sea-derived fungi a new source of novel bioactive compounds? 25, 186–207. <a href="https://doi.org/10.2174/0929867324666170314150121">https://doi.org/10.2174/0929867324666170314150121</a>
5	Medicinal, biochemical and genetic resources	Delbarre-Ladrat, C., Salas, M.L., Siquin, C., Zykwincka, A., Collic-Jouault, S., 2017. Bioprospecting for Exopolysaccharides from Deep-Sea Hydrothermal Vent Bacteria: Relationship between Bacterial Diversity and Chemical Diversity. <i>MICROORGANISMS</i> 5. <a href="https://doi.org/10.3390/microorganisms5030063">https://doi.org/10.3390/microorganisms5030063</a>
5	Medicinal, biochemical and genetic resources	Edrada-Ebel, R.A., Ævarsson, A., Polymenakou, P., Hentschel, U., Carettoni, D., Day, J., Green, D., Hreggviðsson, G.Ó., Harvey, L., McNeil, B., 2018. SeaBioTech: From Seabed to Test-Bed: Harvesting the Potential of Marine Biodiversity for Industrial Biotechnology. <a href="https://doi.org/10.1007/978-3-319-69075-9_12">https://doi.org/10.1007/978-3-319-69075-9_12</a>
5	Medicinal, biochemical and genetic resources	Folkersen, M.V., Fleming, C.M., Hasan, S., 2018. The economic value of the deep sea: A systematic review and meta-analysis. <i>Mar. Policy</i> 94, 71–80. <a href="https://doi.org/https://doi.org/10.1016/j.marpol.2018.05.003">https://doi.org/https://doi.org/10.1016/j.marpol.2018.05.003</a>
5	Medicinal, biochemical and genetic resources	Harden-Davies, H., 2017. Deep-sea genetic resources: New frontiers for science and stewardship in areas beyond national jurisdiction. <i>Deep Sea Res. Part II Top. Stud. Oceanogr.</i> 137, 504–513. <a href="https://doi.org/https://doi.org/10.1016/j.dsr2.2016.05.005">https://doi.org/https://doi.org/10.1016/j.dsr2.2016.05.005</a>
5	Medicinal, biochemical and genetic resources	Jørem, A., Tvedt, M.W., 2014. Bioprospecting in the high seas: Existing rights and obligations in view of a new legal regime for marine areas beyond national jurisdiction. <a href="https://doi.org/10.1163/15718085-12341319">https://doi.org/10.1163/15718085-12341319</a>
5	Medicinal, biochemical and genetic resources	Kushveer, J.S., Rashmi, M., Sarma, V. V, 2021. Chapter 3 - Bioactive compounds from marine-derived fungi and their potential applications, in: Sharma, V.K., Shah, M.P., Parmar, S., Kumar Environment and Nano-technology, A.B.T.-F.B.-P. in S.A. (Eds.), . Academic Press, pp. 91–173. <a href="https://doi.org/https://doi.org/10.1016/B978-0-12-821734-4.00014-9">https://doi.org/https://doi.org/10.1016/B978-0-12-821734-4.00014-9</a>
5	Medicinal, biochemical and genetic resources	Leary, D., 2019. Agreeing to disagree on what we have or have not agreed on: The current state of play of the BBNJ negotiations on the status of marine genetic resources in areas beyond national jurisdiction. <i>Mar. Policy</i> 99, 21–29. <a href="https://doi.org/https://doi.org/10.1016/j.marpol.2018.10.031">https://doi.org/https://doi.org/10.1016/j.marpol.2018.10.031</a>
5	Medicinal, biochemical and genetic resources	Ledoux, J.-B., Antunes, A., 2018. Beyond the beaten path: improving natural products bioprospecting using an eco-evolutionary framework—the case of the octocorals. <a href="https://doi.org/10.1080/07388551.2017.1331335">https://doi.org/10.1080/07388551.2017.1331335</a>

5	Medicinal, biochemical and genetic resources	Ma, D., Fang, Q., Guan, S., 2016. Current legal regime for environmental impact assessment in areas beyond national jurisdiction and its future approaches. <i>Environ. Impact Assess. Rev.</i> 56, 23–30. <a href="https://doi.org/10.1016/j.eiar.2015.08.009">https://doi.org/10.1016/j.eiar.2015.08.009</a>
5	Medicinal, biochemical and genetic resources	Ma, L., Zhang, W.J., Liu, Z.W., Huang, Y.B., Zhang, Q.B., Tian, X.P., Zhang, C.S., Zhu, Y.G., 2021. Complete genome sequence of <i>Streptomyces</i> sp. SCSIO 03032 isolated from Indian Ocean sediment, producing diverse bioactive natural products. <i>Mar. Genomics</i> 55. <a href="https://doi.org/10.1016/j.margen.2020.100803">https://doi.org/10.1016/j.margen.2020.100803</a>
5	Medicinal, biochemical and genetic resources	Moloney, M.G., 2016. Natural Products as a Source for Novel Antibiotics. <i>Trends Pharmacol. Sci.</i> 37, 689–701. <a href="https://doi.org/10.1016/j.tips.2016.05.001">https://doi.org/10.1016/j.tips.2016.05.001</a>
5	Medicinal, biochemical and genetic resources	Ogaki, M.B., Coelho, L.C., Vieira, R., Neto, A.A., Zani, C.L., Alves, T.M.A., Junior, P.A.S., Murta, S.M.F., Barbosa, E.C., Oliveira, J.G., Ceravolo, I.P., Pereira, P.O., Cota, B.B., Viana, R.O., Alves, V.S., Rosa, L.H., 2020. Cultivable fungi present in deep-sea sediments of Antarctica: taxonomy, diversity, and bioprospecting of bioactive compounds. <i>EXTREMOPHILES</i> 24, 227–238. <a href="https://doi.org/10.1007/s00792-019-01148-x">https://doi.org/10.1007/s00792-019-01148-x</a>
5	Medicinal, biochemical and genetic resources	Oldham, P., 2014. Valuing the Deep: Marine Genetic Resources in Areas Beyond National Jurisdiction. <a href="https://doi.org/10.13140/2.1.2612.5605">https://doi.org/10.13140/2.1.2612.5605</a>
5	Medicinal, biochemical and genetic resources	Pan, H.-Q., Hu, J.-C., 2015. Draft genome sequence of the novel strain <i>Pseudomonas</i> sp. 10B238 with potential ability to produce antibiotics from deep-sea sediment. <i>Mar. Genomics</i> 23, 55–57. <a href="https://doi.org/10.1016/j.margen.2015.05.003">https://doi.org/10.1016/j.margen.2015.05.003</a>
5	Medicinal, biochemical and genetic resources	Ribeiro, Â.M., Foote, A.D., Kupczok, A., Frazão, B., Limborg, M.T., Piñeiro, R., Abalde, S., Rocha, S., da Fonseca, R.R., 2017. Marine genomics: News and views. <i>Mar. Genomics</i> 31, 1–8. <a href="https://doi.org/10.1016/j.margen.2016.09.002">https://doi.org/10.1016/j.margen.2016.09.002</a>
5	Medicinal, biochemical and genetic resources	Rodrigo, A.P., Costa, P.M., 2019. The hidden biotechnological potential of marine invertebrates: The Polychaeta case study. <i>Environ. Res.</i> 173, 270–280. <a href="https://doi.org/10.1016/j.envres.2019.03.048">https://doi.org/10.1016/j.envres.2019.03.048</a>
5	Medicinal, biochemical and genetic resources	Santana, K., do Nascimento, L.D., Lima e Lima, A., Damasceno, V., Nahum, C., Braga, R.C., Lameira, J., 2021. Applications of Virtual Screening in Bioprospecting: Facts, Shifts, and Perspectives to Explore the Chemo-Structural Diversity of Natural Products. <a href="https://doi.org/10.3389/fchem.2021.662688">https://doi.org/10.3389/fchem.2021.662688</a>
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5	Medicinal, biochemical and genetic resources	Tortorella, E., Tedesco, P., Esposito, F.P., January, G.G., Fani, R., Jaspars, M., de Pascale, D., 2018. Antibiotics from Deep-Sea Microorganisms: Current Discoveries and Perspectives. <i>Mar. Drugs</i> 16. <a href="https://doi.org/10.3390/md16100355">https://doi.org/10.3390/md16100355</a>
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