

# [Integrating food webs with metabolic networks: modeling contaminant degradation i...](https://assignbuster.com/integrating-food-webs-with-metabolic-networks-modeling-contaminant-degradation-in-marine-ecosystems/)

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A commentary on   
[Bioremediation in marine ecosystems: a computational study combining ecological modeling and flux balance analysis](http://www.frontiersin.org/journal/10.3389/fgene.2014.00319/full)

*by Taffi, M., Paoletti, N., Angione, C., Pucciarelli, S., Marini, M., and Liò, P. (2014). Front. Genet. 5: 319. doi: 10. 3389/fgene. 2014. 00319*

The seas are continuously pervaded by a broad range of contaminants entering the marine environment from polluted soils, the atmosphere, sewage, water transport or river streams ( [Shahidul Islam and Tanaka, 2004](#B18) ). Organic pollutants are of particular concern, because of their tendency to accumulate in specific organisms, thus threatening both ecosystem stability and human health ( [Fleming et al., 2006](#B9) ; [Johnston and Roberts, 2009](#B11) ). Among those, polychlorinated biphenyls (PCBs) are synthetic compounds produced by the chemical industry and found throughout global environments ( [Beyer and Biziuk, 2009](#B3) ). Due to their hydrophobicity, PCBs accumulate in the lipids of marine species, leading to bioaccumulation predominantly at higher trophic levels ( [Perugini et al., 2004](#B17) ). On the other hand, PCBs can be degraded by the sequential anaerobic and aerobic metabolic processes of microorganisms ( [Borja et al., 2005](#B5) ). Consequently, the accumulation and fate of these pollutants within ecosystems depend not only on their uptake by and transfer among marine species, but also on microbial biodegradation. The biostimulation of degrading bacteria or their insertion (bioaugmentation) at contaminated sites may represent a promising strategy for bioremediation ( [Tyagi et al., 2011](#B23) ).

Biomass transfer among species of a food web can be modeled using allometric scaling rules describing body size, consumption and metabolism ( [Yodzis and Innes, 1992](#B25) ; [Berlow et al., 2009](#B2) ). Similarly, the flow of contaminants through a food web can be estimated by mass-balance modeling of chemical transfer and adsorption ( [Wania and Mackay, 1999](#B24) ; [Arnot and Gobas, 2004](#B1) ; [Breivik et al., 2007](#B6) ; [Nichols et al., 2009](#B15) ; [Taffi et al., in press](#B21) ). Such modeling approaches can be complemented by measurements of contaminant concentrations ( [Kelly et al., 2007](#B12) ). Recently, a food web representing the major ecological groups of the Adriatic Sea and their predator-prey interactions ( [Coll et al., 2007](#B7) ) was integrated with PCB concentration data obtained from an extensive literature review ( [Taffi et al., in press](#B21) ). The resulting model allowed prediction of the flow rates of PCBs among ecological groups and reproduced the finding that PCBs accumulate mostly in species at higher trophic levels and with lower total biomass. Further, the model allowed estimation of the fate of contaminants, such as their bioaccumulation in marine species.

The described efforts facilitated generic estimations of contaminant flows in ecosystems, but largely neglected the contribution of microorganisms to pollutant degradation. Specifically, PCBs can be dechlorinated and degraded by a range of bacteria ( [Borja et al., 2005](#B5) ). Thus, biodegradation may be an important factor for the persistence of a pollutant within an ecosystem and, moreover, may provide hints for bioremediation strategies based on the aforementioned bacteria. The uptake, degradation and excretion of compounds by microorganisms can be predicted from the knowledge of their metabolic capabilities using constraint-based approaches ( [Bordbar et al., 2014](#B4) ). Today, detailed metabolic reconstructions are available for a broad range of organisms ( [Monk et al., 2014](#B14) ), including several bacteria known for their bioremediation capabilities, such as *Geobacter* spp. ( [Mahadevan et al., 2011](#B13) ), *Shewanella oneidensis* ( [Fredrickson et al., 2008](#B10) ), and *Pseudomonas putida* ( [Nogales et al., 2008](#B16) ); and new reconstructions for more organisms are published regularly. Thus, an intriguing challenge is the combination of ecological and metabolic modeling approaches to integrate population-level simulations of ecosystems with cellular modeling of microbial metabolism, similar to the previous integration of reactive transport models with metabolic models ( [Fang et al., 2011](#B8) ).

[Taffi et al. (2014)](#B20) have recently integrated a comprehensive food web of the Adriatic Sea with PCB concentration data and a metabolic model of *P. putida* . First, the authors conducted an extensive literature review to complement a food web reconstruction ( [Coll et al., 2007](#B7) ) with data of PCB concentrations among marine species ( [Taffi et al., in press](#B21) ). Next, linear inverse modeling was used to infer unknown contaminant flows and concentrations based on the mass balance principle. Finally, the ecological network was integrated with the genome-scale metabolic network of *P. putida* for constraint-based simulation of microbial PCB degradation. The study integrated two methodologically similar modeling approaches within a reaction-based ecological/microbial network representation, relying on the parallels between representing PCB concentrations and flows on the ecosystem level, and metabolite concentrations and reaction fluxes on the microbial cellular level. Therein, marine species groups resemble the representation of metabolites, while contaminant flows are modeled as reactions. This approach enabled the seamless integration of ecological and metabolic modeling techniques, providing the basis for multi-scale simulations of ecosystems.

The modeling approach was used to predict the influence of different microbial bioremediation strategies on the fate and distribution of PCBs in marine species of the Adriatic Sea. The effect of varying oxygen levels on microbial PCB degradation revealed a tradeoff between PCB uptake and growth of *P. putida* . Further, the impact of different bioremediation scenarios on global and local network indices was assessed. Importantly, the generality of the proposed approach facilitates the integration of measured data, the incorporation of established techniques from ecological and metabolic modeling and the direct application of the methodology to other ecological and microbial networks. Thus, it can be used to guide the selection of appropriate bacteria and consortia ( [Thompson et al., 2005](#B22) ), or the design of genetically engineered bacteria for bioremediation ( [Singh et al., 2011](#B19) ). The approach will stimulate new developments in ecological modeling and offer insights into the multi-level interplay among ecosystems, microbial networks and biodegradation.

## Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## References

Arnot, J. A., and Gobas, F. A. P. C. (2004). A food web bioaccumulation model for organic chemicals in aquatic ecosystems. *Environ. Toxicol. Chem* . 23, 2343–2355. doi: 10. 1897/03-438

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=15511097) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=15511097) | [CrossRef Full Text](http://dx.doi.org/10.1897/03-438) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=J.+A.+Arnot&author=F.+A.+P.+C.+Gobas+&publication_year=2004&title=A+food+web+bioaccumulation+model+for+organic+chemicals+in+aquatic+ecosystems&journal=Environ.+Toxicol.+Chem&volume=23&pages=2343-2355)

Berlow, E. L., Dunne, J. A., Martinez, N. D., Stark, P. B., Williams, R. J., and Brose, U. (2009). Simple prediction of interaction strengths in complex food webs. *Proc. Natl. Acad. Sci. U. S. A* . 106, 187–191. doi: 10. 1073/pnas. 0806823106

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=19114659) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=19114659) | [CrossRef Full Text](http://dx.doi.org/10.1073/pnas.0806823106) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=E.+L.+Berlow&author=J.+A.+Dunne&author=N.+D.+Martinez&author=P.+B.+Stark&author=R.+J.+Williams&author=U.+Brose+&publication_year=2009&title=Simple+prediction+of+interaction+strengths+in+complex+food+webs&journal=Proc.+Natl.+Acad.+Sci.+U.S.A&volume=106&pages=187-191)

Beyer, A., and Biziuk, M. (2009). Environmental fate and global distribution of polychlorinated biphenyls. *Rev. Environ. Contam. Toxicol* . 201, 137–158. doi: 10. 1007/978-1-4419-0032-6\_5

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=19484591) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=19484591) | [CrossRef Full Text](http://dx.doi.org/10.1007/978-1-4419-0032-6_5) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=A.+Beyer&author=M.+Biziuk+&publication_year=2009&title=Environmental+fate+and+global+distribution+of+polychlorinated+biphenyls&journal=Rev.+Environ.+Contam.+Toxicol&volume=201&pages=137-158)

Bordbar, A., Monk, J. M., King, Z. A., and Palsson, B. Ø. (2014). Constraint-based models predict metabolic and associated cellular functions. *Nat. Rev. Genet* . 15, 107–120. doi: 10. 1038/nrg3643

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=24430943) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=24430943) | [CrossRef Full Text](http://dx.doi.org/10.1038/nrg3643) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=A.+Bordbar&author=J.+M.+Monk&author=Z.+A.+King&author=B.+Ø.+Palsson+&publication_year=2014&title=Constraint-based+models+predict+metabolic+and+associated+cellular+functions&journal=Nat.+Rev.+Genet&volume=15&pages=107-120)

Borja, J., Taleon, D. M., Auresenia, J., and Gallardo, S. (2005). Polychlorinated biphenyls and their biodegradation. *Process. Biochem* . 40, 1999–2013. doi: 10. 1016/j. procbio. 2004. 08. 006

[CrossRef Full Text](http://dx.doi.org/10.1016/j.procbio.2004.08.006) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=J.+Borja&author=D.+M.+Taleon&author=J.+Auresenia&author=S.+Gallardo+&publication_year=2005&title=Polychlorinated+biphenyls+and+their+biodegradation&journal=Process.+Biochem&volume=40&pages=1999-2013)

Breivik, K., Sweetman, A., Pacyna, J. M., and Jones, K. C. (2007). Towards a global historical emission inventory for selected PCB congeners - A mass balance approach: 3. An update. *Sci. Total Environ* . 377, 296–307. doi: 10. 1016/j. scitotenv. 2007. 02. 026

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=17395248) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=17395248) | [CrossRef Full Text](http://dx.doi.org/10.1016/j.scitotenv.2007.02.026) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=K.+Breivik&author=A.+Sweetman&author=J.+M.+Pacyna&author=K.+C.+Jones+&publication_year=2007&title=Towards+a+global+historical+emission+inventory+for+selected+PCB+congeners+-+A+mass+balance+approach%3A+3.+An+update&journal=Sci.+Total+Environ&volume=377&pages=296-307)

Coll, M., Santojanni, A., Palomera, I., Tudela, S., and Arneri, E. (2007). An ecological model of the Northern and Central Adriatic Sea: analysis of ecosystem structure and fishing impacts. *J. Mar. Syst* . 67, 119–154. doi: 10. 1016/j. jmarsys. 2006. 10. 002

[CrossRef Full Text](http://dx.doi.org/10.1016/j.jmarsys.2006.10.002) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=M.+Coll&author=A.+Santojanni&author=I.+Palomera&author=S.+Tudela&author=E.+Arneri+&publication_year=2007&title=An+ecological+model+of+the+Northern+and+Central+Adriatic+Sea%3A+analysis+of+ecosystem+structure+and+fishing+impacts&journal=J.+Mar.+Syst&volume=67&pages=119-154)

Fang, Y., Scheibe, T. D., Mahadevan, R., Garg, S., Long, P. E., and Lovley, D. R. (2011). Direct coupling of a genome-scale microbial *in silico* model and a groundwater reactive transport model. *J. Contam. Hydrol* . 122, 96–103. doi: 10. 1016/j. jconhyd. 2010. 11. 007

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=21172725) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=21172725) | [CrossRef Full Text](http://dx.doi.org/10.1016/j.jconhyd.2010.11.007) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=Y.+Fang&author=T.+D.+Scheibe&author=R.+Mahadevan&author=S.+Garg&author=P.+E.+Long&author=D.+R.+Lovley+&publication_year=2011&title=Direct+coupling+of+a+genome-scale+microbial+in+silico+model+and+a+groundwater+reactive+transport+model&journal=J.+Contam.+Hydrol&volume=122&pages=96-103)

Fleming, L. E., Broad, K., Clement, A., Dewailly, E., Elmir, S., Knap, A., et al. (2006). Oceans and human health: emerging public health risks in the marine environment. *Mar. Pollut. Bull* . 53, 545–560. doi: 10. 1016/j. marpolbul. 2006. 08. 012

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=16996542) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=16996542) | [CrossRef Full Text](http://dx.doi.org/10.1016/j.marpolbul.2006.08.012) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=L.+E.+Fleming&author=K.+Broad&author=A.+Clement&author=E.+Dewailly&author=S.+Elmir&author=A.+Knap+&publication_year=2006&title=Oceans+and+human+health%3A+emerging+public+health+risks+in+the+marine+environment&journal=Mar.+Pollut.+Bull&volume=53&pages=545-560)

Fredrickson, J. K., Romine, M. F., Beliaev, A. S., Auchtung, J. M., Driscoll, M. E., Gardner, T. S., et al. (2008). Towards environmental systems biology of Shewanella. *Nat. Rev. Microbiol* . 6, 592–603. doi: 10. 1038/nrmicro1947

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=18604222) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=18604222) | [CrossRef Full Text](http://dx.doi.org/10.1038/nrmicro1947) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=J.+K.+Fredrickson&author=M.+F.+Romine&author=A.+S.+Beliaev&author=J.+M.+Auchtung&author=M.+E.+Driscoll&author=T.+S.+Gardner+&publication_year=2008&title=Towards+environmental+systems+biology+of+Shewanella&journal=Nat.+Rev.+Microbiol&volume=6&pages=592-603)

Johnston, E. L., and Roberts, D. A. (2009). Contaminants reduce the richness and evenness of marine communities: a review and meta-analysis. *Environ. Pollut* . 157, 1745–1752. doi: 10. 1016/j. envpol. 2009. 02. 017

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=19286291) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=19286291) | [CrossRef Full Text](http://dx.doi.org/10.1016/j.envpol.2009.02.017) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=E.+L.+Johnston&author=D.+A.+Roberts+&publication_year=2009&title=Contaminants+reduce+the+richness+and+evenness+of+marine+communities%3A+a+review+and+meta-analysis&journal=Environ.+Pollut&volume=157&pages=1745-1752)

Kelly, B. C., Ikonomou, M. G., Blair, J. D., Morin, A. E., and Gobas, F. A. P. C. (2007). Food web-specific biomagnification of persistent organic pollutants. *Science* 317, 236–239. doi: 10. 1126/science. 1138275

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=17626882) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=17626882) | [CrossRef Full Text](http://dx.doi.org/10.1126/science.1138275) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=B.+C.+Kelly&author=M.+G.+Ikonomou&author=J.+D.+Blair&author=A.+E.+Morin&author=F.+A.+P.+C.+Gobas+&publication_year=2007&title=Food+web-specific+biomagnification+of+persistent+organic+pollutants&journal=Science&volume=317&pages=236-239)

Mahadevan, R., Palsson, B. Ø., and Lovley, D. R. (2011). *In situ* to *in silico* and back: elucidating the physiology and ecology of Geobacter spp. using genome-scale modelling. *Nat. Rev. Microbiol* . 9, 39–50. doi: 10. 1038/nrmicro2456

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=21132020) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=21132020) | [CrossRef Full Text](http://dx.doi.org/10.1038/nrmicro2456) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=R.+Mahadevan&author=B.+Ø.+Palsson&author=D.+R.+Lovley+&publication_year=2011&title=In+situ+to+in+silico+and+back%3A+elucidating+the+physiology+and+ecology+of+Geobacter+spp.+using+genome-scale+modelling&journal=Nat.+Rev.+Microbiol&volume=9&pages=39-50)

Monk, J., Nogales, J., and Palsson, B. Ø. (2014). Optimizing genome-scale network reconstructions. *Nat. Biotechnol* . 32, 447–452. doi: 10. 1038/nbt. 2870

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=24811519) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=24811519) | [CrossRef Full Text](http://dx.doi.org/10.1038/nbt.2870) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=J.+Monk&author=J.+Nogales&author=B.+Ø.+Palsson+&publication_year=2014&title=Optimizing+genome-scale+network+reconstructions&journal=Nat.+Biotechnol&volume=32&pages=447-452)

Nichols, J. W., Bonnell, M., Dimitrov, S. D., Escher, B. I., Han, X., and Kramer, N. I. (2009). Bioaccumulation assessment using predictive approaches. *Integr. Environ. Assess. Manag* . 5, 577–597. doi: 10. 1897/IEAM\_2008-088. 1

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=19775192) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=19775192) | [CrossRef Full Text](http://dx.doi.org/10.1897/IEAM_2008-088.1) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=J.+W.+Nichols&author=M.+Bonnell&author=S.+D.+Dimitrov&author=B.+I.+Escher&author=X.+Han&author=N.+I.+Kramer+&publication_year=2009&title=Bioaccumulation+assessment+using+predictive+approaches&journal=Integr.+Environ.+Assess.+Manag&volume=5&pages=577-597)

Nogales, J., Palsson, B. Ø., and Thiele, I. (2008). A genome-scale metabolic reconstruction of *Pseudomonas putida* KT2440: iJN746 as a cell factory. *BMC Syst. Biol* . 2: 79. doi: 10. 1186/1752-0509-2-79

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=18793442) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=18793442) | [CrossRef Full Text](http://dx.doi.org/10.1186/1752-0509-2-79) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=J.+Nogales&author=B.+Ø.+Palsson&author=I.+Thiele+&publication_year=2008&title=A+genome-scale+metabolic+reconstruction+of+Pseudomonas+putida+KT2440%3A+iJN746+as+a+cell+factory&journal=BMC+Syst.+Biol&volume=2&pages=79)

Perugini, M., Cavaliere, M., Giammarino, A., Mazzone, P., Olivieri, V., and Amorena, M. (2004). Levels of polychlorinated biphenyls and organochlorine pesticides in some edible marine organisms from the Central Adriatic Sea. *Chemosphere* 57, 391–400. doi: 10. 1016/j. chemosphere. 2004. 04. 034

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=15331266) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=15331266) | [CrossRef Full Text](http://dx.doi.org/10.1016/j.chemosphere.2004.04.034) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=M.+Perugini&author=M.+Cavaliere&author=A.+Giammarino&author=P.+Mazzone&author=V.+Olivieri&author=M.+Amorena+&publication_year=2004&title=Levels+of+polychlorinated+biphenyls+and+organochlorine+pesticides+in+some+edible+marine+organisms+from+the+Central+Adriatic+Sea&journal=Chemosphere&volume=57&pages=391-400)

Shahidul Islam, M., and Tanaka, M. (2004). Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis. *Mar. Pollut. Bull* . 48, 624–649. doi: 10. 1016/j. marpolbul. 2003. 12. 004

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=15041420) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=15041420) | [CrossRef Full Text](http://dx.doi.org/10.1016/j.marpolbul.2003.12.004) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=M.+Shahidul+Islam&author=M.+Tanaka+&publication_year=2004&title=Impacts+of+pollution+on+coastal+and+marine+ecosystems+including+coastal+and+marine+fisheries+and+approach+for+management%3A+a+review+and+synthesis&journal=Mar.+Pollut.+Bull&volume=48&pages=624-649)

Singh, J. S., Abhilash, P. C., Singh, H. B., Singh, R. P., and Singh, D. P. (2011). Genetically engineered bacteria: an emerging tool for environmental remediation and future research perspectives. *Gene* 480, 1–9. doi: 10. 1016/j. gene. 2011. 03. 001

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=21402131) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=21402131) | [CrossRef Full Text](http://dx.doi.org/10.1016/j.gene.2011.03.001) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=J.+S.+Singh&author=P.+C.+Abhilash&author=H.+B.+Singh&author=R.+P.+Singh&author=D.+P.+Singh+&publication_year=2011&title=Genetically+engineered+bacteria%3A+an+emerging+tool+for+environmental+remediation+and+future+research+perspectives&journal=Gene&volume=480&pages=1-9)

Taffi, M., Paoletti, N., Angione, C., Pucciarelli, S., Marini, M., and Liò, P. (2014). Bioremediation in marine ecosystems: a computational study combining ecological modeling and flux balance analysis. *Front. Genet* . 5: 319. doi: 10. 3389/fgene. 2014. 00319

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=25309577) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=25309577) | [CrossRef Full Text](http://dx.doi.org/10.3389/fgene.2014.00319)

Taffi, M., Paoletti, N., Liò, P., Pucciarelli, S., and Marini, M. (in press). Bioaccumulation modelling and sensitivity analysis for discovering key players in contaminated food webs: the case study of PCBs in the Adriatic Sea. *Ecol. Modell* . doi: 10. 1016/j. ecolmodel. 2014. 11. 030

[CrossRef Full Text](http://dx.doi.org/10.1016/j.ecolmodel.2014.11.030) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=M.+Taffi&author=N.+Paoletti&author=P.+Liò&author=S.+Pucciarelli&author=M.+Marini+&publication_year=in press&title=Bioaccumulation+modelling+and+sensitivity+analysis+for+discovering+key+players+in+contaminated+food+webs%3A+the+case+study+of+PCBs+in+the+Adriatic+Sea&journal=Ecol.+Modell)

Thompson, I. P., Van Der Gast, C. J., Ciric, L., and Singer, A. C. (2005). Bioaugmentation for bioremediation: the challenge of strain selection. *Environ. Microbiol* . 7, 909–915. doi: 10. 1111/j. 1462-2920. 2005. 00804. x

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=15946288) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=15946288) | [CrossRef Full Text](http://dx.doi.org/10.1111/j.1462-2920.2005.00804.x) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=I.+P.+Thompson&author=C.+J.+Van+Der+Gast&author=L.+Ciric&author=A.+C.+Singer+&publication_year=2005&title=Bioaugmentation+for+bioremediation%3A+the+challenge+of+strain+selection&journal=Environ.+Microbiol&volume=7&pages=909-915)

Tyagi, M., Da Fonseca, M. M. R., and De Carvalho, C. C. C. R. (2011). Bioaugmentation and biostimulation strategies to improve the effectiveness of bioremediation processes. *Biodegradation* 22, 231–241. doi: 10. 1007/s10532-010-9394-4

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=20680666) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=20680666) | [CrossRef Full Text](http://dx.doi.org/10.1007/s10532-010-9394-4) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=M.+Tyagi&author=M.+M.+R.+Da+Fonseca&author=C.+C.+C.+R.+De+Carvalho+&publication_year=2011&title=Bioaugmentation+and+biostimulation+strategies+to+improve+the+effectiveness+of+bioremediation+processes&journal=Biodegradation&volume=22&pages=231-241)

Wania, F., and Mackay, D. (1999). The evolution of mass balance models of persistent organic pollutant fate in the environment. *Environ. Pollut* . 100, 223–240. doi: 10. 1016/S0269-7491(99)00093-7

[Pubmed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=15093120) | [Pubmed Full Text](http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?db=pubmed&cmd=prlinks&retmode=ref&id=15093120) | [CrossRef Full Text](http://dx.doi.org/10.1016/S0269-7491(99)00093-7) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=F.+Wania&author=D.+Mackay+&publication_year=1999&title=The+evolution+of+mass+balance+models+of+persistent+organic+pollutant+fate+in+the+environment&journal=Environ.+Pollut&volume=100&pages=223-240)

Yodzis, P., and Innes, S. (1992). Body size and consumer-resource dynamics. *Am. Nat* . 139, 1151–1175. doi: 10. 1086/285380

[CrossRef Full Text](http://dx.doi.org/10.1086/285380) | [Google Scholar](http://scholar.google.com/scholar_lookup?author=P.+Yodzis&author=S.+Innes+&publication_year=1992&title=Body+size+and+consumer-resource+dynamics&journal=Am.+Nat&volume=139&pages=1151-1175)