

**Table S1** Relative abundance of sensitive and tolerant microbes at genus level in soils contaminated by various combinations of lanthanum (La), cerium (Ce), and fluorine (F)

Relative abundance of microbes (%)		CK	LC1	LC2	LC3	LC4	LC5	CF1	CF2	CF3	CF4	CF5	LF1	LF2	LF3	LF4	LF5	LCF1	LCF2	LCF3	LCF4	LCF5
phylum	genus																					
<b>Abditibacteriota</b>	<b>Abditibacterium</b>	0.003	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.07	0.09	0.00	0.00	0.03	0.10	0.15	0.00	0.00	0.04	0.05	0.21
<b>Nitrospirota</b>	<b>Nitrospira</b>	0.0004	0.001	0.001	0.001	0.0001	0.00	0.001	0.001	0.001	0.0001	0.00	0.001	0.001	0.0002	0.00	0.0002	0.0012	0.0005	0.0002	0.00	0.00
	<b>c_4-29-1</b>	0.0001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	<b>Gemmatomacidae</b>	0.010	0.006	0.007	0.005	0.002	0.002	0.010	0.017	0.012	0.006	0.003	0.011	0.010	0.011	0.016	0.007	0.007	0.010	0.007	0.002	0.003
	<b>Isoosphaeraceae</b>	0.005	0.004	0.011	0.011	0.001	0.002	0.004	0.009	0.009	0.004	0.002	0.004	0.004	0.005	0.008	0.005	0.003	0.004	0.004	0.002	0.003
	<b>WD2101</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0002	0.00	0.00	0.00	0.00	0.001	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Planctomycetota</b>	<b>SM1A02</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.0002	0.0001	0.0001	0.00	0.0001	0.001	0.001	0.00	0.00	0.00	0.00	0.00
	<b>Aquisphaera</b>	0.0007	0.0005	0.0007	0.0006	0.0002	0.0003	0.0006	0.0011	0.0008	0.0010	0.0003	0.0011	0.0007	0.0011	0.0009	0.0006	0.0005	0.0009	0.0008	0.0004	0.0006
	<b>AKAU3564</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.0001	0.00	0.00	0.00	0.00	0.00	0.00	0.0001
	<b>BD7-11</b>	0.0001	0.0001	0.00	0.00	0.00	0.00	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.00	0.00	0.0001	0.0001	0.0001	0.0001	0.00	0.0001	0.0001
	<b>Singulisphaera</b>	0.0004	0.0001	0.0003	0.0003	0.0001	0.0009	0.0003	0.0007	0.0011	0.0004	0.0008	0.0003	0.0004	0.0005	0.0004	0.0012	0.0003	0.0004	0.0006	0.0002	0.0014
	<b>I-8</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.00	0.00	0.00	0.00
	<b>Isoosphaera</b>	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.00	0.00	0.00	0.003	0.0001	0.0001	0.00	0.0001	0.0001	0.00	0.00	0.00	0.0001	0.0001	0.0001
	<b>AKYG587</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00003	0.00	0.00	0.00	0.00	0.00
	<b>Phycisphaeraceae</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.0001	0.00	0.00	0.00
	<b>Tundrisphaera</b>	0.0004	0.0001	0.0001	0.00	0.00	0.00	0.0002	0.0003	0.0004	0.0001	0.00	0.00	0.00	0.0001	0.0001	0.0000	0.00	0.0000	0.0000	0.00	0.00
<b>Dependentia</b>	<b>Babelliaceae</b>	0.00	0.0001	0.00	0.00	0.00	0.00	0.0001	0.0001	0.0001	0.00	0.00	0.00	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	<b>Vermiphilaceae</b>	0.00	0.00	0.0001	0.00	0.00	0.00	0.0001	0.0004	0.0002	0.0001	0.0001	0.0001	0.0001	0.0003	0.0001	0.0002	0.0001	0.0001	0.0005	0.00	0.0001
	<b>Babellales</b>	0.00	0.00	0.00	0.0001	0.00	0.00	0.00	0.00	0.0001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001
	<b>UBA12411</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.00	0.00	0.00	0.00	0.00	0.00
	<b>UBA12409</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00003	0.00	0.00003	0.00	0.00
<b>Mortierellomycota</b>	<b>Mortierella</b>	0.0623	0.0480	0.0255	0.0087	0.0061	0.0071	0.0304	0.0309	0.0446	0.0257	0.0230	0.0150	0.0174	0.0401	0.0427	0.0121	0.0351	0.0132	0.0212	0.0082	0.0129
	<b>Mortierellomycota</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.00	0.00	0.00	0.00
<b>Zoopagomycota</b>	<b>Syncephalis</b>	0.00	0.0002	0.0002	0.00	0.00	0.00	0.0002	0.0001	0.0001	0.00	0.0002	0.0002	0.00	0.00	0.0001	0.0001	0.0001	0.00	0.00	0.00	0.00
	<b>Acaulopage</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.00	0.00	0.00	0.00	0.00	0.0001	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Piptoccephalidaceae</b>	<b>Piptoccephalidaceae</b>	0.0001	0.0001	0.00	0.00	0.00	0.0001	0.00	0.0002	0.00	0.0001	0.00	0.0001	0.00	0.0001	0.0001	0.00	0.0001	0.0001	0.00	0.00	0.00
	<b>Gemmatimonas</b>	0.0087	0.0064	0.0116	0.0095	0.0214	0.0221	0.0209	0.0261	0.0418	0.0297	0.0663	0.0193	0.0235	0.0226	0.0456	0.0649	0.0246	0.0202	0.0336	0.0709	0.0550
<b>Gemmatimonadota</b>	<b>Gemmatimonadaceae</b>	0.0054	0.0071	0.0082	0.0065	0.0085	0.0070	0.0130	0.0169	0.0243	0.0182	0.0257	0.0128	0.0171	0.0207	0.0312	0.0381	0.0183	0.0224	0.0343	0.0148	
	<b>S0134</b>	0.0007	0.0005	0.0006	0.0006	0.0005	0.0006	0.0006	0.0007	0.0005	0.0004	0.0003	0.0003	0.0009	0.0006	0.0011	0.0005	0.0008	0.0006	0.0009	0.0007	
	<b>Roseisolibacter</b>	0.0001	0.0001	0.0001	0.0001	0.0001	0.00	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.00	0.0001	0.0001	0.0001	0.0001	0.0005
<b>Bacteroidota</b>	<b>Longimicrobiaceae</b>	0.0005	0.0003	0.0003	0.0001	0.0003	0.0002	0.0004	0.0005	0.0003	0.0003	0.0004	0.0003	0.0004	0.0004	0.0006	0.0003	0.0006	0.0006	0.0005	0.0008	0.0004
	<b>Mucilaginibacter</b>	0.0013	0.0011	0.0012	0.0011	0.0027	0.0066	0.0022	0.0005	0.0023	0.0032	0.0060	0.0006	0.0014	0.0025	0.0029	0.0043	0.0013	0.0011	0.0036	0.0084	0.0088
	<b>Edaphobaculum</b>	0.0002	0.0004	0.0004	0.0001	0.0033	0.0008	0.0005	0.0001	0.0029	0.0010	0.0044	0.0001	0.0002	0.0009	0.0012	0.0016	0.0004	0.0001	0.0007	0.0034	0.0040
	<b>Flavisolibacter</b>	0.0004	0.0001	0.00	0.0002	0.0010	0.0015	0.0005	0.0002	0.0020	0.0022	0.0082	0.0002	0.0002	0.0018	0.0021	0.0067	0.0004	0.0004	0.0011	0.0031	0.0066
	<b>env OPS_17</b>	0.00	0.00	0.0002	0.0015	0.0002	0.0007	0.00	0.00	0.0002	0.0001	0.0001	0.0001	0.00	0.00	0.0001	0.0002	0.00	0.00	0.00	0.00	0.0002
	<b>Chitinophagaceae</b>	0.0005	0.0010	0.0042	0.0007	0.0017	0.0028	0.0005	0.0011	0.0023	0.0030	0.0219	0.0004	0.0003	0.0020	0.0037	0.0194	0.0013	0.0021	0.0013	0.0083	0.0274
	<b>Chitinophagales</b>	0.0001	0.0002	0.0004	0.0002	0.0013	0.0012	0.0002	0.0006	0.0015	0.0014	0.0016	0.0009	0.0006	0.0014	0.0004	0.0016	0.0014	0.0009	0.0015	0.0011	0.0009
	<b>Flavobacterium</b>	0.00	0.0002	0.0001	0.0001	0.00	0.0001	0.00	0.00	0.0002	0.00	0.00	0.00	0.0004	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0002
	<b>Kapabacteriales</b>	0.0002	0.0002	0.0002	0.0001	0.0002	0.0001	0.0003	0.0001	0.0014	0.0005	0.0001	0.0004	0.0001	0.0004	0.00	0.0001	0.0007	0.0001	0.0010	0.0004	0.00
	<b>Sporocytophaga</b>	0.0001	0.0001	0.00	0.00	0.00	0.00	0.0001	0.00	0.00	0.0002	0.0001	0.00	0.00	0.0001	0.0004	0.0002	0.0003	0.0013	0.00	0.0001	0.0003
<b>Puia</b>	0.0001	0.0001	0.00	0.00	0.00	0.00	0.0001	0.00	0.00	0.0002	0.0001	0.00	0.00	0.0001	0.0004	0.0002	0.0003	0.0013	0.00	0.0001	0.0003	
<b>Myxococcota</b>	<b>Haliangium</b>	0.0018	0.0009	0.0004	0.0007	0.0014	0.0010	0.0024	0.0027	0.0042	0.0015	0.0019	0.0019	0.0026	0.0038	0.0014	0.0025	0.0025	0.0021	0.0029	0.0022	0.0020
	<b>Anaeromyxobacter</b>	0.0004	0.0001	0.0004	0.0002	0.0004	0.0001	0.0006	0.0004	0.0005	0.0002	0.0004	0.0006	0.0003	0.0003	0.0002	0.0006	0.0002	0.0005	0.0001	0.0003	0.0003
	<b>P3OB-42</b>	0.0005	0.0001	0.0004	0.0001	0.0001	0.0002	0.0002	0.0001	0.0003	0.0003	0.0003	0.0003	0.0003	0.0001	0.0002	0.0002	0.0002	0.0004	0.0001	0.0004	0.0002
	<b>Pajaroellobacter</b>	0.0009	0.0006	0.0006	0.0005	0.0010	0.0005	0.0006	0.0012	0.0018	0.0003	0.0081	0.0006	0.0006	0.0012	0.0014	0.0038	0.0014	0.0009	0.0010	0.0052	0.0095
	<b>mle1-27</b>	0.0001	0.0001	0.00	0.00	0.0001	0.0001	0.0001	0.0001	0.00	0.0001	0.00	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.00	0.00</		

**Table S2** RDA analysis of sensitive and tolerant of microbial communities with chemical fractions of La, Ce and F under different interactions.

Tr	Sensitive microbial community								Tolerant microbial community								
	bacteria				fungus				bacteria				Fungus				
	RDA1	RDA2	r <sup>2</sup>	Pr(>r)	RDA1	RDA2	r <sup>2</sup>	Pr(>r)	RDA1	RDA2	r <sup>2</sup>	Pr(>r)	RDA1	RDA2	r <sup>2</sup>	Pr(>r)	
LC	La_WS	-0.6351	-0.7725	0.5692	0.002 **	0.4543	-0.8908	0.9034	0.001 ***	0.8877	-0.4604	0.4126	0.027 *	0.9417	0.3366	0.2485	0.1140
	La_EX	-0.6338	-0.7735	0.5261	0.004 **	0.4411	-0.8975	0.8534	0.001 ***	0.8791	-0.4766	0.4997	0.010 **	0.9744	0.2249	0.3006	0.0690
	La_CAR	-0.8404	-0.5420	0.5591	0.002 **	0.5561	-0.8311	0.8982	0.001 ***	0.7945	-0.6072	0.4737	0.012 *	0.9787	0.2051	0.2027	0.1810
	La_FeMn	-0.7354	-0.6776	0.5863	0.002 **	0.4832	-0.8755	0.9075	0.001 ***	0.8525	-0.5227	0.4314	0.021 *	0.9576	0.2880	0.2530	0.1060
	La_ORG	-0.5393	-0.8421	0.4378	0.002 **	0.3311	-0.9436	0.7260	0.001 ***	0.9118	-0.4107	0.6251	0.002 **	0.9869	0.1614	0.4304	0.020 *
	La_RES	0.7158	0.6983	0.3787	0.022 *	-0.5182	0.8553	0.6619	0.002 **	-0.7938	0.6082	0.6700	0.001 ***	-0.9935	0.1139	0.3851	0.035 *
	Ce_WS	-0.5514	-0.8342	0.5106	0.008 **	0.4273	-0.9041	0.8780	0.001 ***	0.9132	-0.4076	0.4726	0.012 *	0.9408	0.3390	0.2552	0.1140
	Ce_EX	-0.5488	-0.8360	0.5523	0.004 **	0.3916	-0.9202	0.8461	0.001 ***	0.9118	-0.4107	0.4643	0.015 *	0.9590	0.2835	0.3198	0.0520
	Ce_CAR	-0.6998	-0.7144	0.5574	0.002 **	0.4708	-0.8823	0.9089	0.001 ***	0.8708	-0.4916	0.4527	0.017 *	0.9525	0.3046	0.2530	0.1060
	Ce_FeMn	-0.7426	-0.6697	0.5621	0.002 **	0.4915	-0.8709	0.9155	0.001 ***	0.8547	-0.5191	0.4510	0.018 *	0.9544	0.2985	0.2384	0.1250
	Ce_ORG	-0.7373	-0.6756	0.4895	0.004 **	0.4623	-0.8867	0.8821	0.001 ***	0.8930	-0.4501	0.6067	0.003 **	0.9502	0.3117	0.2460	0.1230
	Ce_RES	-0.8833	-0.4688	0.6009	0.002 **	0.5866	-0.8099	0.8798	0.001 ***	0.7124	-0.7018	0.3171	0.0760	0.9605	0.2783	0.1646	0.2350
CF	Ce_WS	-0.9993	-0.0378	0.9349	0.001 ***	0.4988	0.8667	0.2474	0.1100	0.9792	0.2027	0.8803	0.001 ***	-0.6662	0.7458	0.5601	0.005 **
	Ce_EX	-0.9943	0.1068	0.8819	0.001 ***	0.4287	0.9035	0.3742	0.034 *	0.8943	0.4474	0.8702	0.001 ***	-0.6387	0.7695	0.6989	0.002 **
	Ce_CAR	-0.9997	-0.0250	0.9423	0.001 ***	0.5022	0.8648	0.2503	0.1080	0.9818	0.1898	0.8805	0.001 ***	-0.6714	0.7411	0.5734	0.004 **
	Ce_FeMn	-1.0000	-0.0064	0.9433	0.001 ***	0.4849	0.8746	0.2420	0.1160	0.9816	0.1911	0.8860	0.001 ***	-0.6609	0.7505	0.5875	0.003 **
	Ce_ORG	-0.9937	0.1125	0.8864	0.001 ***	0.4394	0.8983	0.3089	0.044 *	0.9140	0.4057	0.9010	0.001 ***	-0.6378	0.7702	0.7017	0.001 ***
	Ce_RES	-0.9727	-0.2322	0.8893	0.001 ***	0.6686	0.7437	0.1206	0.3960	0.9794	-0.2018	0.8723	0.001 ***	-0.7539	0.6570	0.3072	0.0620
	F_WS	-0.9961	-0.0884	0.8813	0.001 ***	0.6527	0.7576	0.1074	0.4390	0.9979	-0.0647	0.9352	0.001 ***	-0.7144	0.6997	0.4451	0.012 *
	F_EX	-0.9805	0.1967	0.8933	0.001 ***	0.5172	0.8559	0.1674	0.2480	0.9626	0.2708	0.9556	0.001 ***	-0.6629	0.7487	0.7529	0.001 ***
	F_FeMn	-0.9967	0.0818	0.9045	0.001 ***	0.5550	0.8319	0.1863	0.2110	0.9780	0.2085	0.9438	0.001 ***	-0.6832	0.7302	0.6606	0.001 ***
	F_ORG	-0.9989	0.0463	0.8581	0.001 ***	0.6526	0.7577	0.2714	0.044 *	0.9495	0.3139	0.9350	0.001 ***	-0.7488	0.6628	0.6666	0.001 ***
	F_RES	-0.9579	0.2873	0.8872	0.001 ***	0.4038	0.9149	0.2688	0.1010	0.8910	0.4540	0.9181	0.001 ***	-0.6258	0.7800	0.8398	0.001 ***
	Ce_WS	-0.9993	-0.0378	0.9349	0.001 ***	0.4988	0.8667	0.2474	0.1100	0.9792	0.2027	0.8803	0.001 ***	-0.6662	0.7458	0.5601	0.005 **
LF	La_WS	0.9999	-0.0124	0.9294	0.001 ***	-0.8308	-0.5566	0.0127	0.8940	0.9950	0.1000	0.9592	0.001 ***	0.8924	-0.4513	0.5905	0.009 **
	La_EX	0.9986	0.0528	0.8948	0.001 ***	-0.4581	0.8889	0.0085	0.9390	0.9999	-0.0123	0.9635	0.001 ***	0.8968	-0.4425	0.7057	0.002 **
	La_CAR	0.9910	0.1340	0.9364	0.001 ***	0.2108	0.9775	0.0164	0.8910	0.9983	0.0579	0.8953	0.001 ***	0.8309	-0.5565	0.7116	0.001 ***
	La_FeMn	0.9949	0.1006	0.9315	0.001 ***	-0.2919	0.9565	0.0080	0.9460	0.9991	0.0430	0.9300	0.001 ***	0.8641	-0.5033	0.7048	0.001 ***
	La_ORG	0.9848	0.1740	0.9208	0.001 ***	0.2548	0.9670	0.0616	0.6240	0.9985	0.0542	0.8542	0.001 ***	0.8408	-0.5414	0.7260	0.001 ***
	La_RES	0.8307	0.5567	0.6740	0.001 ***	-0.9366	0.3505	0.5556	0.004 **	0.7848	0.6198	0.4346	0.023 *	0.9939	0.1107	0.5776	0.004 **
	F_WS	0.9995	0.0311	0.8284	0.001 ***	0.4119	0.9112	0.0316	0.7780	0.9957	-0.0932	0.9535	0.001 ***	0.8794	-0.4761	0.7029	0.002 **
	F_EX	1.0000	0.0092	0.8126	0.001 ***	-0.4533	0.8914	0.0231	0.8390	0.9955	-0.0949	0.9763	0.001 ***	0.9451	-0.3268	0.7239	0.001 ***
	F_FeMn	0.9904	0.1379	0.8897	0.001 ***	0.4379	0.8990	0.0399	0.7340	0.9999	-0.0164	0.8872	0.001 ***	0.8223	-0.5691	0.7390	0.001 ***
	F_ORG	0.9994	0.0358	0.8273	0.001 ***	-0.2289	0.9735	0.0532	0.6560	0.9986	-0.0525	0.9441	0.001 ***	0.9533	-0.3021	0.7275	0.001 ***
	F_RES	0.9844	0.1760	0.8754	0.001 ***	-0.5521	0.8338	0.0963	0.045 *	1.0000	0.0015	0.8889	0.001 ***	0.9588	-0.2842	0.8141	0.001 ***
	Ce_WS	0.9999	-0.0124	0.9294	0.001 ***	-0.8308	-0.5566	0.0127	0.8940	0.9950	0.1000	0.9592	0.001 ***	0.8924	-0.4513	0.5905	0.009 **
LCF	La_WS	1.0000	-0.0015	0.9155	0.001 ***	1.0000	-0.0024	0.6638	0.001 ***	0.9862	0.1653	0.9290	0.001 ***	0.8576	-0.5144	0.9210	0.001 ***
	La_EX	0.9920	-0.1261	0.8671	0.001 ***	1.0000	-0.0035	0.6769	0.001 ***	0.9838	0.1791	0.9730	0.001 ***	0.9348	-0.3553	0.8533	0.001 ***
	La_CAR	0.9792	-0.2031	0.9300	0.001 ***	0.9997	0.0266	0.5576	0.003 **	0.9999	0.0152	0.9801	0.001 ***	0.8720	-0.4895	0.8515	0.001 ***
	La_FeMn	0.9814	-0.1919	0.9375	0.001 ***	0.9960	0.0893	0.6061	0.002 **	0.9980	0.0641	0.9918	0.001 ***	0.8901	-0.4557	0.8814	0.001 ***
	La_ORG	0.9859	-0.1673	0.9312	0.001 ***	0.9991	0.0436	0.6106	0.002 **	0.9978	0.0663	0.9865	0.001 ***	0.8857	-0.4643	0.8744	0.001 ***
	La_RES	0.9884	0.1522	0.9274	0.001 ***	0.9863	0.1650	0.6935	0.001 ***	0.9763	-0.2167	0.8075	0.001 ***	0.5973	-0.8020	0.7537	0.001 ***
	Ce_WS	0.9877	-0.1562	0.9211	0.001 ***	0.9989	-0.0470	0.5500	0.004 **	0.9998	0.0225	0.9611	0.001 ***	0.8505	-0.5261	0.8685	0.001 ***
	Ce_EX	0.9979	-0.0648	0.8999	0.001 ***	0.9997	0.0261	0.7233	0.001 ***	0.9808	0.1948	0.9829	0.001 ***	0.9176	-0.3974	0.8898	0.001 ***
	Ce_CAR	0.9993	-0.0382	0.9293	0.001 ***	0.9993	0.0369	0.7160	0.001 ***	0.9857	0.1684	0.9755	0.001 ***	0.8886	-0.4588	0.9119	0.001 ***
	Ce_FeMn	0.9962	-0.0877	0.9218	0.001 ***	0.9998	0.0224	0.6905	0.001 ***	0.9921	0.1255	0.9809	0.001 ***	0.8955	-0.4452	0.8746	0.001 ***
	Ce_ORG	0.9998	-0.0216	0.9118	0.001 ***	0.9999	0.0162	0.7312	0.001 ***	0.9794	0.2019	0.9724	0.001 ***	0.9015	-0.4328	0.9041	0.001 ***
	Ce_RES	0.8811	-0.4730	0.8307	0.001 ***	0.9995	-0.0317	0.2136	0.1820	0.9470	-0.3213	0.8862	0.001 ***	0.7736	-0.6337	0.5873	0.001 ***
F_WS	0.9624	-0.2718	0.8293	0.001 ***	0.9997	-0.0257	0.5369	0.004 **	0.9874	0.1581	0.9427	0.001 ***	0.9542	-0.2992	0.8313	0.001 ***	
F_EX	0.9966	-0.0824	0.8643	0.001 ***	1.0000	0.0085	0.7156	0.001 ***	0.9720	0.2350	0.9825	0.001 ***	0.9397	-0.3419	0.8853	0.001 ***	
F_FeMn	0.9996	0.0292	0.7886	0.001 ***	0.9978	0.0661	0.8321	0.001 ***	0.9215	0.3884	0.9753	0.001 ***	0.9721	-0.2344	0.8742	0.001 ***	
F_ORG	0.9644	-0.2645	0.8531	0.001 ***	1.0000	0.0064	0.5457	0.004 **	0.9955	0.0948	0.9438	0.001 ***	0.9380	-0.3466	0.7991	0.001 ***	
F_RES	0.9998	-0.0202	0.8744	0.001 ***	1.0000	0.0039	0.7760	0.001 ***	0.9812	0.1932	0.9542	0.001 ***	0.9261	-0.3772	0.8168	0.001 ***	

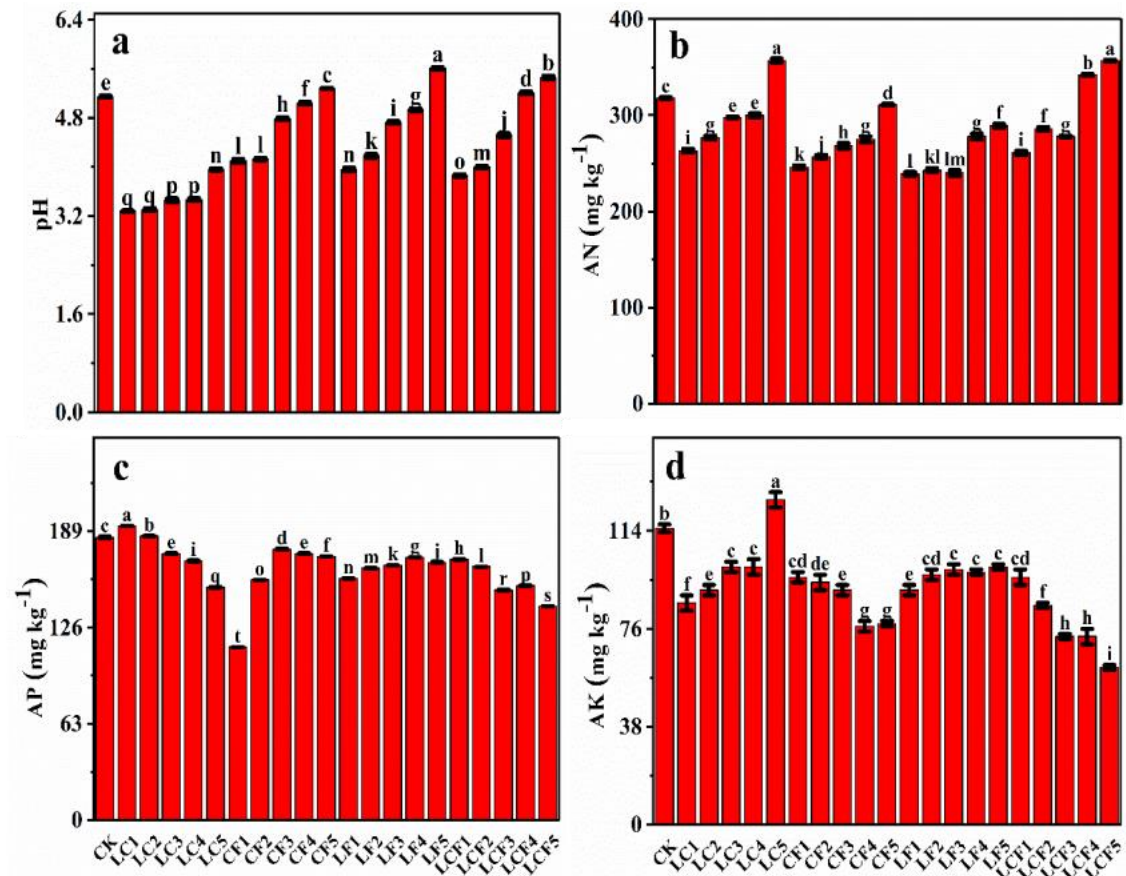
Abbreviations: La, lanthanum; Ce, cerium; F, fluorine; CK, control; LC, La + Ce contaminated soil; CF, Ce + F contaminated soil; LF, La + F contaminated soil; LCF, La + Ce + F contaminated soil; WS, water-soluble form; EX,

exchangeable form; CAR carbonate-bound form; FeMn, iron-manganese-bound form; ORG, organic-bound form; RES, residual form.

**Table S3** Relative abundance change (%) of bacterial and fungal microbes in soil microbial community.

Taxon	LC1	LC2	LC3	LC4	LC5	CF1	CF2	CF3	CF4	CF5	LF1	LF2	LF3	LF4	LF5	LCF1	LCF2	LCF3	LCF4	LCF5
B1	-0.07	-0.12	0.13	-0.51	-0.29	-0.23	-0.12	-0.36	-0.10	-0.68	-0.16	-0.26	-0.26	-0.46	-0.48	-0.20	-0.22	-0.42	-0.74	-0.58
B2	-0.28	-0.23	-0.36	0.10	-0.16	-0.02	-0.17	0.16	0.05	0.93	-0.24	-0.01	0.23	0.46	0.40	-0.10	-0.13	0.13	0.73	0.41
B3	0.05	0.11	0.17	0.40	0.07	-0.01	-0.12	-0.16	-0.50	-0.29	-0.26	0.07	-0.17	-0.30	-0.22	-0.01	0.01	-0.02	-0.06	-0.09
B4	0.71	0.38	0.40	-0.28	0.53	0.68	0.53	0.00	0.61	-0.42	1.08	0.28	-0.08	-0.32	-0.20	0.39	0.29	0.31	-0.55	-0.13
B5	-0.33	-0.43	-0.48	-0.55	-0.61	-0.13	0.22	0.29	0.48	0.05	0.61	0.09	0.34	0.52	0.26	-0.01	-0.10	0.20	0.03	0.10
B6	-0.31	-0.21	-0.35	-0.12	-0.17	-0.26	-0.31	-0.27	-0.28	-0.26	-0.34	-0.07	0.02	0.04	-0.33	-0.14	0.04	0.00	0.15	-0.05
B7	-0.49	-0.43	-0.55	-0.83	-0.71	-0.17	0.50	0.33	-0.37	-0.70	-0.08	-0.17	0.01	0.39	-0.21	-0.36	-0.09	-0.30	-0.78	-0.58
B8	-0.15	0.02	-0.02	0.79	0.78	1.04	1.65	2.98	1.85	4.51	0.95	1.47	1.65	3.65	5.16	1.62	1.36	2.42	5.31	3.28
B9	3.47	7.87	3.57	14.62	12.72	0.58	0.07	1.38	0.72	-0.40	0.19	0.89	0.48	-0.12	0.16	2.23	2.05	0.76	0.86	-0.31
B10	3.03	-0.04	1.33	-0.47	-0.46	0.73	0.33	-0.10	0.01	-0.10	0.06	0.62	-0.19	0.33	0.01	0.14	2.43	0.49	-0.80	-0.60
B11	-0.49	-0.41	-0.58	-0.22	-0.37	0.07	0.12	0.66	-0.34	1.22	-0.13	-0.10	0.27	-0.03	0.72	0.21	0.05	0.15	0.72	1.58
B12	1.26	4.14	0.90	3.87	3.76	1.50	0.79	5.82	2.71	12.18	0.60	0.82	3.04	5.57	9.23	3.35	3.18	3.48	10.28	15.70
B13	-0.54	-0.17	-0.53	-0.70	-0.66	-0.09	0.21	0.65	-0.49	-0.78	0.02	-0.17	0.03	-0.16	-0.61	-0.32	-0.16	-0.37	-0.83	-0.70
B14	-0.50	-0.56	-0.50	-0.25	-0.65	-0.35	-0.57	-0.58	-0.73	-0.66	-0.50	-0.61	-0.58	-0.59	-0.60	-0.21	-0.56	-0.71	-0.59	-0.64
B15	-0.81	-0.38	-0.73	-0.68	-0.80	-0.65	-0.48	-0.46	-0.70	-0.63	-0.53	-0.18	-0.44	-0.39	-0.63	-0.51	-0.61	-0.58	-0.46	-0.46
B16	-0.75	-0.42	-0.74	-0.89	-0.90	-0.47	0.06	1.06	0.05	0.17	-0.31	-0.70	0.88	0.14	-0.02	-0.68	-0.41	-0.51	-0.60	1.81
B17	-0.67	-0.50	-0.65	-0.88	-0.55	-0.33	0.79	1.15	0.60	-0.27	-0.26	-0.30	0.42	0.20	0.60	-0.63	-0.24	0.49	-0.63	0.82
B18	-0.66	-0.32	-0.56	-0.36	-0.88	-0.37	-0.01	0.14	-0.55	-0.79	-0.12	0.42	-0.42	-0.43	-0.60	-0.18	0.19	-0.20	-0.27	-0.55
B19	-0.02	0.10	-0.16	-0.17	-0.79	0.14	0.26	-0.15	-0.32	-0.50	-0.18	0.48	-0.04	-0.48	-0.81	-0.35	0.23	-0.38	-0.36	-0.38
B20	0.55	0.18	-0.08	-0.82	-1.00	0.87	-0.04	-0.07	-0.92	-0.95	0.17	0.07	-0.61	-0.89	-0.67	1.02	-0.06	-0.74	-0.88	-0.96
B21	-0.91	-0.75	-0.72	-0.91	-0.77	-0.08	-0.61	-0.62	-0.43	-0.83	0.32	-0.55	-0.79	-0.35	-0.65	-0.05	-0.77	-0.73	-0.91	-0.66
B22	-0.61	-0.63	-0.59	-0.87	-0.86	-0.26	1.27	0.93	-0.16	-0.51	-0.31	1.62	-0.13	0.66	1.03	0.59	2.34	-0.46	-0.45	0.14
B23	0.68	0.37	-1.00	-0.38	-0.78	1.16	-0.40	-0.56	2.35	-0.22	-0.78	0.46	-0.01	-0.39	-0.31	0.69	-0.57	3.27	-0.56	-0.77
B24	32.16	1.05	-0.49	-0.04	-0.75	-1.00	-0.07	-0.75	-0.48	-1.00	-1.00	-0.51	-0.77	-1.00	-0.46	-0.26	-0.26	-1.00	-0.49	-0.21
B25	-0.33	0.88	-0.65	-1.00	-0.31	-0.06	-0.36	-1.00	-0.64	-0.58	-0.65	-0.67	-0.68	-1.00	0.11	0.02	-0.66	1.04	-0.65	-0.64
B26	-1.00	0.25	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.22	-1.00	1.04	-1.00	1.11	-1.00
B27	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	2.26	13.21	18.52	25.22	-1.00	-1.00	7.38	26.64	43.25	-1.00	0.38	10.05	12.55	59.12
B28	7.52	-1.00	-1.00	-1.00	-1.00	9.64	4.44	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	56.34	-1.00	-1.00	-1.00	-1.00
G1	0.00	-0.09	0.08	-0.05	0.00	0.03	-0.02	-0.02	0.01	0.06	0.11	0.03	-0.01	-0.09	0.09	0.00	0.04	0.01	-0.02	-0.02
G2	-0.20	-0.20	-0.38	-0.42	0.03	-0.18	-0.21	0.13	-0.16	-0.30	-0.47	-0.03	-0.08	-0.21	-0.46	-0.14	-0.19	-0.36	-0.12	-0.30
G3	-0.25	-0.62	-0.87	-0.90	-0.89	-0.55	-0.51	-0.32	-0.61	-0.65	-0.78	-0.72	-0.38	-0.34	-0.81	-0.47	-0.81	-0.68	-0.87	-0.80
G4	3.75	14.35	3.94	15.56	5.75	1.71	2.78	2.06	0.54	0.17	1.08	1.52	1.93	7.29	0.10	1.14	2.03	1.39	0.60	0.52
G5	0.19	4.46	1.08	4.79	2.75	4.63	14.76	2.99	12.62	8.26	0.19	5.92	9.06	17.98	7.59	11.87	6.63	21.14	27.58	29.71
G6	0.12	-0.87	-0.82	-0.92	-0.76	0.74	0.68	-0.49	0.23	0.06	0.35	-0.75	-0.53	-0.70	-0.38	-0.57	-0.44	0.00	-0.36	-0.21
G7	-0.90	-0.53	-0.87	-0.74	-0.96	-1.00	1.04	-0.92	-0.49	-0.47	-0.76	-0.79	-0.72	-0.65	-0.85	-0.23	-1.00	-0.85	-0.54	-0.62
G8	1.32	-0.56	-0.35	-0.26	-0.31	-0.51	0.00	0.71	0.15	-0.17	0.24	-0.18	1.42	1.57	-0.75	-0.35	0.07	0.38	0.01	-0.23
G9	-0.41	-0.47	-0.90	-0.86	-0.62	-0.42	-0.04	-0.66	-0.55	-0.32	-0.59	-0.73	-0.47	-0.73	-0.52	0.12	-0.64	-1.00	-1.00	-0.93
G10	3.08	0.67	-0.75	0.52	0.45	2.15	0.90	0.34	0.54	-0.20	0.51	1.84	-0.45	2.65	7.29	0.48	-0.14	-0.46	0.06	0.60
G11	0.41	-0.77	2.31	-0.59	0.84	-1.00	-1.00	5.83	3.99	0.13	-0.12	-0.42	-1.00	3.14	0.25	-1.00	0.55	-1.00	-1.00	-0.36
G12	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
G13	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
G14	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	0.34	-1.00	1.93	-1.00	-1.00	-1.00	-1.00	0.33	-0.06	-1.00	-1.00	2.82	-1.00	0.44
G15	-1.00	7.20	-1.00	2.73	-1.00	3.51	-1.00	4.35	-1.00	-1.00	0.98	-1.00	-1.00	-1.00	-1.00	-1.00	5.99	-1.00	-1.00	-1.00

Abbreviations: La, lanthanum; Ce, cerium; F, fluorine; LC, La + Ce contaminated soil; CF, Ce + F contaminated soil; LF, La + F contaminated soil; LCF, La + Ce + F contaminated soil; B1, Chloroflexi; B2, Proteobacteria; B3, Actinobacteriota; B4, WPS\_2; B5, Acidobacteriota; B6, Firmicutes; B7, Planctomycetota; B8, Gemmatimonadota; B9, Patescibacteria; B10, Cyanobacteria; B11, Myxococcota; B12, Bacteroidota; B13, unclassified-k-norank-d-bacteria; B14, Bdellovibrionota; B15, Desulfobacterota; B16, Armatimonadota; B17, Verrucomicrobiota; B18, Sumerlaeota; B19, RCP2-54; B20, Nitrospirota; B21, Elusimicrobiota; B22, Dependientiae; B23, Halanaerobiaeota; B24, Deinococcota; B25, GAL15; B26, WS4; B27, Abditibacteriota; B28, FCPU426. Fungal phyla: G1, Ascomycota; G2, Basidiomycota; G3, Mortierellomycota; G4, unclassified\_k fungi; G5, Chytridiomycota; G6, Mucoromycota; G7, Olpidiomycota; G8, Glomeromycota; G9, Zoopagomycota; G10, Rozellomycota; G11, Basidiobolomycota; G12, Blastocladiomycota; G13, Kickxellomycota; G14, Calcarisporiellomycota; G15, Monoblepharomycota.



**Fig. S1** Conventional chemical properties of the combined pollution soils based on various combinations of lanthanum (La), cerium (Ce), and fluorine (F), showing variations in the levels of pH (a), hydrolysable nitrogen (b), available phosphorus (c), and available potassium (d). CK, control; LC, La + Ce contaminated soil; CF, Ce + F contaminated soil; LF, La + F contaminated soil; LCF, La + Ce + F contaminated soil. Different lowercase letters above bars indicate significant difference among different groups, and the error bars represent the standard deviations based on three biological replicates of each group.