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Title page- supplementary information

Rare earth oxide nanoparticles promote soil microbial antibiotic resistance by selectively enriching antibiotic resistance genes

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The supplementary information has 43 pages including 6 tables and 3 figures.

Table S1. The basic properties of soils used in this study.

Property	Soil type		
	Black soil	Fluvo-aquic soil	Red soil
pH	6.25 ± 0.05	7.89 ± 0.02	5.80 ± 0.03
Total carbon (g kg^{-1})	10.49 ± 0.03	7.11 ± 0.01	7.17 ± 0.01
Total nitrogen (g kg^{-1})	1.02 ± 0.01	1.06 ± 0.01	0.94 ± 0.01
NH_4^+-N (mg kg^{-1})	11.31 ± 0.25	2.31 ± 0.17	9.63 ± 0.02
NO_3^--N (mg kg^{-1})	25.32 ± 1.02	9.25 ± 0.18	10.87 ± 0.38

Values represent mean ± s.d., n=4

Table S2. Physiochemical properties of the nanoparticles used in this study.

Property	Nanoparticle type		
	Nano-La_2O_3	Nano-Nd_2O_3	Nano-Gd_2O_3
Size (nm)	25 ± 5	35 ± 7	27 ± 2
Size in deionized H_2O (nm)	589 ± 16	308 ± 8	532 ± 100
Zeta potential in deionized H_2O (mV)	9 ± 1	26 ± 1	11 ± 1

Values represent mean ± s.d.

Table S3. 202 sets of primers used in this study.

	Assay Name	Forward primer	Reverse primer	Antibiotic resistance	Resistance mechanism
1	16S rRNA	GGGTTGCGCTCGTTGC	ATGGYTGTCGTCAGCTCGTG		
2	aac	CCCTGCGTTGTGGCTATGT	TTGGCCACGCCAATCC	Aminoglycoside	Antibiotic deactivation
3	aac(6')-Ib-01	GTTTGAGAGGCAAGGTACCGTAA	GAATGCCTGGCGTGTTTGA	Aminoglycoside	Antibiotic deactivation
4	aac(6')-Ib-02	CGTCGCCGAGCAACTTG	CGGTACCTTGCCTCTCAAACC	Aminoglycoside	Antibiotic deactivation
5	aac(6')-Ib-03	AGAAGCACGCCCGACACTT	GCTCTCCATTCAGCATTGCA	Aminoglycoside	Antibiotic deactivation
6	aac(6')-II	CGACCCGACTCCGAA	GCACGAATCCTGCCT	Aminoglycoside	Antibiotic

		CAA	TCTCA		deactivation
7	aacC	CGTCACTTATTCGATGCCCTTAC	GTCGGGCGCGGCATA	Aminoglycoside	Antibiotic deactivation
8	aacC1	GGTCGTGAGTTCGGAGACGTA	GCAAGTTCCCGAGGTAATCG	Aminoglycoside	Antibiotic deactivation
9	aacC2	ACGGCATTCTCGATTGCTTT	CCGAGCTTCACGTAAGCATTT	Aminoglycoside	Antibiotic deactivation
10	aacC4	CGGCGTGGGACACGAT	AGGGAACCTTTGCCATCAACT	Aminoglycoside	Antibiotic deactivation
11	aadA-01	GTTGTGCACGACGACATCATT	GGCTCGAAGATACCTGCAAGAA	Aminoglycoside	Antibiotic deactivation
12	aadA-02	CGAGATTCTCCGCGCTGTA	GCTGCCATTCTCCAAATTGC	Aminoglycoside	Antibiotic deactivation
13	aadA1	AGCTAAGCGCGAACT	TGGCTCGAAGATACC	Aminoglycoside	Antibiotic

		GCAAT	TGCAA		deactivation
14	aadA2-01	ACGGCTCCGCAGTGGAT	GGCCACAGTAACCAACAAATCA	Aminoglycoside	Antibiotic deactivation
15	aadA2-02	CTTGTCGTGCATGACGACATC	TCGAAGATACCCGCAAGAATG	Aminoglycoside	Antibiotic deactivation
16	aadA2-03	CAATGACATTCTTGCGGGTATC	GACCTACCAAGGCAACGCTATG	Aminoglycoside	Antibiotic deactivation
17	aadA5-01	ATCACGATCTTGCGATTTTGCT	CTGCGGATGGGCCTAGAAG	Aminoglycoside	Antibiotic deactivation
18	aadA5-02	GTTCTTGCTCTTGCTCGCATT	GATGCTCGGCAGGCAAAC	Aminoglycoside	Antibiotic deactivation
19	aadA9-01	CGCGGCAAGCCTATCTTG	CAAATCAGCGACCGCAGACT	Aminoglycoside	Antibiotic deactivation
20	aadA9-02	GGATGCACGCTTGGA	CCTCTAGCGGCCGGA	Aminoglycoside	Antibiotic

		TGAA	GTATT		deactivation
21	aadD	CCGACAACATTTCTACCATCCTT	ACCGAAGCGCTCGTCGTATA	Aminoglycoside	Antibiotic deactivation
22	aph(2')-Id	TGAGCAGTATCATAAGTTGAGTGAAAAG	GACAGAACAATCAATCTCTATGGAATG	Aminoglycoside	Antibiotic deactivation
23	aphA1	TGAACAAGTCTGGAAAGAAATGCA	CCTATTAATTTCCCCTCGTCAAAAA	Aminoglycoside	Antibiotic deactivation
24	aphA3-01	AAAAGCCCGAAGAGGAACTTG	CATCTTTCACAAAGATGTTGCTGTCT	Aminoglycoside	Antibiotic deactivation
25	aphA3-02	CGGAATTGAAAAAACTGATCGAA	ATACCGGCTGTCCGTCATTT	Aminoglycoside	Antibiotic deactivation
26	strA	CCGGTGGCATTTGAGAAAAA	GTGGCTCAACCTGCGAAAAG	Aminoglycoside	Antibiotic deactivation
27	strB	GCTCGGTCGTGAGAA	CAATTTCGGTCGCCT	Aminoglycoside	Antibiotic

		CAATCT	GGTAGT		deactivation
28	catA1	GGGTGAGTTTCACCAGTTTTGATT	CACCTTGTCGCCTTGCGTATA	FCA	Antibiotic deactivation
29	catB3	GCACTCGATGCCTTCCAAAA	AGAGCCGATCCAAACGTCAT	FCA	Antibiotic deactivation
30	catB8	CACTCGACGCCTTCCAAAG	CCGAGCCTATCCAGACATCATT	FCA	Antibiotic deactivation
31	cfr	GCAAAATTCAGAGCAAGTTACGAA	AAAATGACTCCCAACCTGCTTTAT	FCA	Antibiotic deactivation
32	cmlA1-01	TAGGAAGCATCGGAACGTTGAT	CAGACCGAGCACGACTGTTG	FCA	Efflux pump
33	cmlA1-02	AGGAAGCATCGGAACGTTGA	ACAGACCGAGCACGACTGTTG	FCA	Efflux pump
34	cmx(A)	GCGATCGCCATCCTC	TCGACACGGAGCCTT	FCA	Efflux pump

		TGT	GGT		
35	floR	ATTGTCTTCACGGTGTCCGTTA	CCGCGATGTCGTCGAACT	FCA	Efflux pump
36	qnrA	AGGATTTCTCACGCCAGGATT	CCGCTTTCAATGAAACTGCAA	FCA	Other
37	ereA	CCTGTGGTACGGAGAATTCATGT	ACCGCATTCGCTTTGCTT	MLSB	Antibiotic deactivation
38	ereB	GCTTTATTTCAGGAGGCGGAAT	TTTTAAATGCCACAGCACAGAATC	MLSB	Antibiotic deactivation
39	lnuA	TGACGCTCAACACACTCAAAAA	TTCATGCTTAAGTTCCATACGTGAA	MLSB	Antibiotic deactivation
40	mphA-01	CTGACGCGCTCCGTGTT	GGTGGTGCATGGCGATCT	MLSB	Antibiotic deactivation
41	mphA-02	TGATGACCCTGCCAT	TTCGCGAGCCCCTCT	MLSB	Antibiotic

		CGA	TC		deactivation
42	mphB	CGCAGCGCTTGATCTTGTAG	TTACTGCATCCATACGCTGCTT	MLSB	Antibiotic deactivation
43	vatC	CGGAAATTGGGAACGATGTT	GCAATAATAGCCCCGTTTCCTA	MLSB	Antibiotic deactivation
44	vatE-01	GGTGCCATTATCGGAGCAAAT	TTGGATTGCCACCGACAAT	MLSB	Antibiotic deactivation
45	vatE-02	GACCGTCCTACCAGGCGTAA	TTGGATTGCCACCGACAATT	MLSB	Antibiotic deactivation
46	vgb	AGGGAGGGTATCCATGCAGAT	ACCAAATGCGCCCGTTT	MLSB	Antibiotic deactivation
47	matA/mel	TAGTAGGCAAGCTCGGTGTTGA	CCTGTGCTATTTTAAGCCTTGTTTCT	MLSB	Efflux pump
48	mefA	CCGTAGCATTGGAAC	AAACGGAGTATAAG	MLSB	Efflux pump

		AGCTTTT	AGTGCTGCAA		
49	msrA	CTGCTAACACAAGTACGATTCCAAAT	TCAAGTAAAGTTGTCTTACCTACACCATT	MLSB	Efflux pump
50	oleC	CCCGGAGTCGATGTTCGA	GCCGAAGACGTACACGAACAG	MLSB	Efflux pump
51	vgaA	CGAGTATTGTGGAAAGCAGCTAGTT	CCCGTACCGTTAGAGCCGATA	MLSB	Efflux pump
52	vgaB	TAAAAGAGAATAAGGCGCAAGGA	TGTTTAGTAGCATGTTGCATTTTCC	MLSB	Efflux pump
53	erm(34)	GCGCGTTGACGACGATTT	TGGTCATACTCGACGGCTAGAAC	MLSB	Cellular protection
54	erm(36)	GGCGGACCGACTTGCAT	TCTGCGTTGACGACGGTTAC	MLSB	Cellular protection
55	ermA	TTGAGAAGGGATTTG	ATATCCATCTCCACC	MLSB	Cellular

		CGAAAAG	ATTAATAGTAAACC		protection
56	ermA/ermTR	ACATTTTACCAAGGAACTTGTGGAA	GTGGCATGACATAAACCTTCATCA	MLSB	Cellular protection
57	ermB	TAAAGGGCATTTAACGACGAAACT	TTTATACCTCTGTTTGTTAGGGAATTGAA	MLSB	Cellular protection
58	ermC	TTTGAAATCGGCTCAGGAAAA	ATGGTCTATTTCAATGGCAGTTACG	MLSB	Cellular protection
59	ermF	CAGCTTTGGTTGAACATTTACGAA	AAATTCCTAAAATCACAACCGACAA	MLSB	Cellular protection
60	ermK	GTTTGATATTGGCATTGTCAGAGAAA	ACCATTGCCGAGTCCACTTT	MLSB	Cellular protection
61	ermX	GCTCAGTGGTCCCCATGGT	ATCCCCCCGTCAACGTTT	MLSB	Cellular protection
62	ermY	TTGTCTTTGAAAGTG	TAACGCTAGAGAACG	MLSB	Cellular

		AAGCAACAGT	ATTTGTATTGAG		protection
63	pikR2	TCGTGGGCCAGGTGAAGA	TTCCCCTTGCCGGTGAA	MLSB	Cellular protection
64	acrA-01	CAACGATCGGACGGGTTTC	TGGCGATGCCACCGTACT	Multidrug	Efflux pump
65	acrA-02	GGTCTATCACCCTACGCGCTATC	GCGCGCACGAACATACC	Multidrug	Efflux pump
66	acrA-03	CAGACCCGCATCGCATATT	CGACAATTTCGCGCTCATG	Multidrug	Efflux pump
67	acrA-04	TACTTTGCGCGCCATCTTC	CGTGCGCGAACGAACAT	Multidrug	Efflux pump
68	acrA-05	CGTGCGCGAACGAACA	ACTTTGCGCGCCATCTTC	Multidrug	Efflux pump
69	acrB	AGTCGGTGTTCGCCG	CAAGGAAACGAACG	Multidrug	Efflux pump

		TTAAC	CAATACC		
70	acrF	GCGGCCAGGCACAAAA	TACGCTCTTCCCACGGTTTC	Multidrug	Efflux pump
71	acrR	GCGCTGGAGACACGACAAC	GCCTTGCTGCGAGAACAAA	Multidrug	Efflux pump
72	adeA	CAGTTCGAGCGCCTATTTCTG	CGCCCTGACCGACCAAT	Multidrug	Efflux pump
73	ceoA	ATCAACACGGACCAGGACAAG	GGAAAGTCCGCTCACGATGA	Multidrug	Efflux pump
74	emrD	CTCAGCAGTATGGTGGTAAGCATT	ACCAGGCGCCGAAGAAC	Multidrug	Efflux pump
75	marR	GCGGCGTACTGGTGAAGCTA	TGCCCTGGTCGTTGATGA	Multidrug	Efflux pump
76	mdetl1	ATACAGCAGTGGATA	TGCATAAGGTGAATG	Multidrug	Efflux pump

		TTGGTTTAATTGT	TTCCATGA		
77	mdtE/yhiU	CGTCGGCGCACTCGTT	TCCAGACGTTGTACGGTAACCA	Multidrug	Efflux pump
78	mepA	ATCGGTCGCTCTTCGTTCAC	ATAAATAGGATCGAGCTGCTGGAT	Multidrug	Efflux pump
79	mexA	AGGACAACGCTATGCAACGAA	CCGGAAAGGGCCGAAAT	Multidrug	Efflux pump
80	mexE	GGTCAGCACCGACAAGGTCTAC	AGCTCGACGTACTTGAGGAACAC	Multidrug	Efflux pump
81	mexF	CCGCGAGAAGGCCAAGA	TTGAGTTCGGCGGTGATGA	Multidrug	Efflux pump
82	mtrD	TGCGCGTAGTCGTTCATCTC	CGTTCCAATTTCCTGATGATTG	Multidrug	Efflux pump
83	oprD	ATGAAGTGGAGCGCC	GGCCACGGCGAACTG	Multidrug	Efflux pump

		ATTG	A		
84	oprJ	ACGAGAGTGGCGTCGACAA	AAGGCGATCTCGTTGAGGAA	Multidrug	Efflux pump
85	qacEΔ1-01	TCGCAACATCCGCATTAAAA	ATGGATTTCAGAACCAGAGAAAGAAA	Multidrug	Efflux pump
86	qacEΔ1-02	CCCCTTCCGCCGTTGT	CGACCAGACTGCATAAGCAACA	Multidrug	Efflux pump
87	qacH-01	GTGGCAGCTATCGCTTGGAT	CCAACGAACGCCCACAA	Multidrug	Efflux pump
88	qacH-02	CATCGTGCTTGTGGCAGCTA	TGAACGCCCAGAAGTCTAGTTTT	Multidrug	Efflux pump
89	rarD	GCGGGTGTGGTCACTACGAT	AGCGTTGGGCCGATATACTG	Multidrug	Efflux pump
90	sdeB	CACTACCGCTTCCGC	TGAAAAAACGGGAA	Multidrug	Efflux pump

		ACTTAA	AAGTCCAT		
91	tolC-01	GGCCGAGAACCTGATGCA	AGACTTACGCAATTCCGGGTTA	Multidrug	Efflux pump
92	tolC-02	CAGGCAGAGAACCTGATGCA	CGCAATTCCGGGTTGCT	Multidrug	Efflux pump
93	tolC-03	GCCAGGCAGAGAACCTGATG	CGCAATTCCGGGTTGCT	Multidrug	Efflux pump
94	ttgA	ACGCCAATGCCAAACGATT	GTCACGGCGCAGCTTGA	Multidrug	Efflux pump
95	ttgB	TCGCCCTGGATGTACACCTT	ACCATTGCCGACATCAACAAC	Multidrug	Efflux pump
96	yceE/mdtG	TGGCACAAAATATCTGGCAGTT	TTGTGTGGCGATAAGAGCATTAG	Multidrug	Efflux pump
97	yceL/mdtH-01	TCGGGATGGTGGGCA	CGATAACCGAGCCGA	Multidrug	Efflux pump

		AT	TGTAGA		
98	yceL/mdtH-02	CGCGTGAAACCTTAAGTGCTT	AGACGGCTAAACCCCATATAGCT	Multidrug	Efflux pump
99	yidY/mdtL	GCAGTTGCATATCGCCTTCTC	CTTCCCGGCAAACAGCAT	Multidrug	Efflux pump
100	bacA	CGGCTTCGTGACCTCGTT	ACAATGCGATACCAGGCAAAT	Other	Antibiotic deactivation
101	sat4	GAATGGGCAAAGCATAAAAACTTG	CCGATTTTGAAACCACAATTATGATA	Other	Antibiotic deactivation
102	pncA	GCAATCGAGGCGGTGTTC	TTGCCGCAGCCAATTCA	Other	Unkown
103	uidA	AACCACGCGTCTGTTGACTG	CCCGGTTGCCAGAGGTG	Other	Unkown
104	dfrA1	GGAATGGCCCTGATA	AGTCTTGCGTCCAAC	Sulfonamide	Antibiotic

		TTCCA	CAACAG		deactivation
105	dfrA12	CCTCTACCGAACCGTCACACA	GCGACAGCGTTGAAACAACTAC	Sulfonamide	Antibiotic deactivation
106	folA	CGAGCAGTTCCTGCCAAAG	CCCAGTCATCCGGTTCATAATC	Sulfonamide	Antibiotic deactivation
107	sul1	CAGCGCTATGCGCTCAAG	ATCCCGCTGCGCTGAGT	Sulfonamide	Cellular protection
108	sul2	TCATCTGCCAAACTCGTCGTTA	GTCAAAGAACGCCGCAATGT	Sulfonamide	Cellular protection
109	tetA	GCTGTTTGTTCTGCCGGAAA	GGTTAAGTTCCTTGAACGCAAACT	Tetracycline	Efflux pump
110	tetB-01	AGTGCGCTTTGGATGCTGTA	AGCCCCAGTAGCTCCTGTGA	Tetracycline	Efflux pump
111	tetB-02	GCCCAGTGCTGTTGT	TGAAAGCAAACGGC	Tetracycline	Efflux pump

		TGTCAT	CTAAATACA		
112	tetC-01	CATATCGCAATACATGCGAAAAA	AAAGCCGCGGTAAATAGCAA	Tetracycline	Efflux pump
113	tetC-02	ACTGGTAAGGTAAACGCCATTGTC	ATGCATAAACCAGCCATTGAGTAAG	Tetracycline	Efflux pump
114	tetD-01	TGCCGCGTTTGATTACACA	CACCAGTGATCCCGGAGATAA	Tetracycline	Efflux pump
115	tetD-02	TGTCATCGCGCTGGTGATT	CATCCGCTTCCGGGAGAT	Tetracycline	Efflux pump
116	tetE	TTGGCGCTGTATGCAATGAT	CGACGACCTATGCGATCTGA	Tetracycline	Efflux pump
117	tetG-01	TCAACCATTGCCGATTCGA	TGGCCCGGCAATCATG	Tetracycline	Efflux pump
118	tetG-02	CATCAGCGCCGGTCT	CCCCATGTAGCCGAA	Tetracycline	Efflux pump

		TATG	CCA		
119	tetH	TTTGGGTCATCTTACCAGCATTAA	TTGCGCATTATCATCGACAGA	Tetracycline	Efflux pump
120	tetL	AGCCCGATTTATTCAAGGAATTG	CAAATGCTTTCCCCCTGTTCT	Tetracycline	Efflux pump
121	tetR-01	CGCGATAGACGCCTTCGA	TCCTGACAACGAGCCTCCTT	Tetracycline	Efflux pump
122	tetR-02	CGCGATGGAGCAAAAGTACAT	AGTGAAAAACCTTGTTGGCATAAAA	Tetracycline	Efflux pump
123	tetV	GCGGGAACGACGATGTATATC	CCGCTATCTCACGACCATGAT	Tetracycline	Efflux pump
124	tet(32)	CCATTACTTCGGACAACGGTAGA	CAATCTCTGTGAGGGCATTTAACA	Tetracycline	Cellular protection
125	tet(36)-01	AGAATACTCAGCAGA	TGGTAGGTCGATAAC	Tetracycline	Cellular

		GGTCAGTTCCT	CCGAAAAT		protection
126	tet(36)-02	TGCAGGAAAGACCTCCATTACAG	CTTTGTCCACACTTCCACGTACTATG	Tetracycline	Cellular protection
127	tetM-01	CATCATAGACACGCCAGGACATAT	CGCCATCTTTTGCAGAAATCA	Tetracycline	Cellular protection
128	tetM-02	TAATATTGGAGTTTTAGCTCATGTTGATG	CCTCTCTGACGTTCTAAAAGCGTATTAT	Tetracycline	Cellular protection
129	tetO	ATGTGGATACTACAACGCATGAGATT	TGCCTCCACATGATATTTTTCCT	Tetracycline	Cellular protection
130	tetPB-01	ACACCTGGACACGCTGATTTT	ACCGTCTAGAACGCGGAATG	Tetracycline	Cellular protection
131	tetPB-02	TGATACACCTGGACACGCTGAT	CGTCCAAAACGCGGAATG	Tetracycline	Cellular protection
132	tetPB-03	TGGGCGACAGTAGGC	TGACCCTACTGAAAC	Tetracycline	Cellular

		TTAGAA	ATTAGAAATATACCT		protection
133	tetQ	CGCCTCAGAAGTAAGTTCATACACTAAG	TCGTTCATGCGGATATTATCAGAAT	Tetracycline	Cellular protection
134	tetS	TTAAGGACAAACTTTCTGACGACATC	TGTCTCCCATTGTTCTGGTTCA	Tetracycline	Cellular protection
135	tetT	CCATATAGAGGTTCCACCAAATCC	TGACCCTATTGGTAGTGGTTCTATTG	Tetracycline	Cellular protection
136	tetW	ATGAACATTCCCACCGTTATCTTT	ATATCGGCGGAGAGCTTATCC	Tetracycline	Cellular protection
137	tet(35)	ACCCCATGACGTACCTGTAGAGA	CAACCCACACTGGCTACCAGTT	Tetracycline	Other
138	tetX	AAATTTGTTACCGACACGGAAGTT	CATAGCTGAAAAAATCCAGGACAGTT	Tetracycline	Other
139	vanB-01	TTGTCGGCGAAGTGG	AGCCTTTTTCCGGCT	Vancomycin	Cellular

		ATCA	CGTT		protection
140	vanB-02	CCGGTCGAGGAACGAAATC	TCCTCCTGCAAAAAAAGATCAAC	Vancomycin	Cellular protection
141	vanC-01	ACAGGGATTGGCTATGAACCAT	TGACTGGCGATGATTTGACTATG	Vancomycin	Cellular protection
142	vanC-02	CCTGCCACAATCGATCGTT	CGGCTTCATTCGGCTTGATA	Vancomycin	Cellular protection
143	vanC2/vanC3	TTTGACTGTCGGTGCTTGTGA	TCAATCGTTTCAGGCAATGG	Vancomycin	Cellular protection
144	vanHB	GAGGTTTCCGAGGCGACAA	CTCTCGGCGGCAGTCGTAT	Vancomycin	Cellular protection
145	vanRA-01	CCCTTACTCCCACCGAGTTTT	TTCGTCGCCCCATATCTCAT	Vancomycin	Cellular protection
146	vanRA-02	CCACTCCGGCCTTGT	GCTAACCACATTCCC	Vancomycin	Cellular

		CATT	CTTGTTTT		protection
147	vanRB	GCCCTGTCGGATGACGAA	TTACATAGTCGTCTGCCTCTGCAT	Vancomycin	Cellular protection
148	vanSB	GCGCGGCAAATGACAAC	TTTGCCATTTTATTCGCACTGT	Vancomycin	Cellular protection
149	vanSC	ATCAACTGCGGGAGAAAAGTCT	TCCGCTGTTCCGCTTCTT	Vancomycin	Cellular protection
150	vanTC-01	CACACGCATTTTTTCCCATCTAG	CAGCCAACAGATCATCAAAACAA	Vancomycin	Cellular protection
151	vanTC-02	ACAGTTGCCGCTGGTGAAG	CGTGGCTGGTCGATCAAAA	Vancomycin	Cellular protection
152	vanTE	GTGGTGCCAAGGAAGTTGCT	CGTAGCCACCGCAAAAAAAT	Vancomycin	Cellular protection
153	vanTG	CGTGTAGCCGTTCCG	CGGCATTACAGGTAT	Vancomycin	Cellular

		TTCTT	ATCTGGAAA		protection
154	vanWB	CGGACAAAGATACCCCCTATAAAG	AAATAGTAAATTGCTCATCTGGCACAT	Vancomycin	Cellular protection
155	vanWG	ACATTTTCATTTTGGCAGCTTGTAC	CCGCCATAAGAGCCTACAATCT	Vancomycin	Cellular protection
156	vanXB	AGGCACAAAATCGAAGATGCTT	GGGTATGGCTCATCAATCAACTT	Vancomycin	Cellular protection
157	vanYB	GGCTAAAGCGGAAGCAGAAA	GATATCCACAGCAAGACCAAGCT	Vancomycin	Cellular protection
158	vanYD-01	AAGGCGATACCCTGACTGTCA	ATTGCCGGACGGAAGCA	Vancomycin	Cellular protection
159	vanYD-02	CAAACGGAAGAGAGGTCACTTACA	CGGACGGTAATAGGGACTGTTC	Vancomycin	Cellular protection
160	ampC/blaDHA	TGGCCGCAGCAGAA	CCGTTTTATGCACCC	β-lactam	Antibiotic

		AGA	AGGAA		deactivation
161	ampC-01	TGGCGTATCGGGTCAATGT	CTCCACGGGCCAGTTGAG	β-lactam	Antibiotic deactivation
162	ampC-02	GCAGCACGCCCCGTAA	TGTACCCATGATGCGCGTACT	β-lactam	Antibiotic deactivation
163	ampC-03	AACAAAAGATCCCCGGTATGG	ACGCCCGTAAATGTTTTGCT	β-lactam	Antibiotic deactivation
164	ampC-04	TCCGGTGACGCGACAGA	CAGCACGCCGGTGAAAGT	β-lactam	Antibiotic deactivation
165	ampC-05	CTGTTCGAGCTGGGTTCTATAAGTAAA	CAGTATCTGGTCACCGGATCGT	β-lactam	Antibiotic deactivation
166	ampC-06	CCGCTCAAGCTGGACCATAC	CCATATCCTGCACGTTGGTTT	β-lactam	Antibiotic deactivation
167	bla1	GCAAGTTGAAGCGA	TACCAGTATCAATCG	β-lactam	Antibiotic

		AAGAAAAGA	CATATACACCTAA		deactivation
168	blaCMY2-01	AAAGCCTCATGGGTGCATAAA	ATAGCTTTTGTTTGCCAGCATCA	β-lactam	Antibiotic deactivation
169	blaCMY2-02	GCGAGCAGCCTGAAGCA	CGGATGGGCTTGTCCTCTT	β-lactam	Antibiotic deactivation
170	blaCTX-M-01	GGAGGCGTGACGGCTTTT	TTCAGTGCGATCCAGACGAA	β-lactam	Antibiotic deactivation
171	blaCTX-M-02	GCCGCGGTGCTGAAGA	ATCGGATTATAGTTAACCAGGTCAGATTT	β-lactam	Antibiotic deactivation
172	blaGES	GCAATGTGCTCAACGTTCAAG	GTGCCTGAGTCAATTCTTTCAAAG	β-lactam	Antibiotic deactivation
173	bla-L1	CACCGGGTTACCAGCTGAAG	GCGAAGCTGCGCTTGTAGTC	β-lactam	Antibiotic deactivation
174	blaMOX/blaCMY	CTATGTCAATGTGCC	GGCTTGTCCTCTTTC	β-lactam	Antibiotic

		GAAGCA	GAATAGC		deactivation
175	blaOXA1/blaOXA30	CGGATGGTTTGAAGGGTTTATTAT	TCTTGGCTTTTATGCTTGATGTTAA	β-lactam	Antibiotic deactivation
176	blaOXA10-01	CGCAATTATCGGCCTAGAAACT	TTGGCTTTCCGTCCCATTT	β-lactam	Antibiotic deactivation
177	blaOXA10-02	TCAACAAATCGCCAGAGA	TCCCACACCAGAAAAACCA	β-lactam	Antibiotic deactivation
178	blaOXY	CGTTCAGGCGGCAGGTT	GCCGCGATATAAGATTTGAGAATT	β-lactam	Antibiotic deactivation
179	blaPAO	CGCCGTACAACCGGTGAT	GAAGTAATGCGGTTCTCCTTTCA	β-lactam	Antibiotic deactivation
180	blaPSE	TTGTGACCTATTCCCCTGTAATAGAA	TGCGAAGCACGCATCATC	β-lactam	Antibiotic deactivation
181	blaROB	GCAAAGGCATGACG	CGCGCTGTTGTCGCT	β-lactam	Antibiotic

		ATTGC	AAA		deactivation
182	blaSHV	TCCCATGATGAGCACCTTTAAA	TTCGTCACCGGCATCCA	β-lactam	Antibiotic deactivation
183	blaTEM	AGCATCTTACGGATGGCATGA	TCCTCCGATCGTTGTCAGAAGT	β-lactam	Antibiotic deactivation
184	blaTLA	ACACTTTGCCATTGCTGTTTATGT	TGCAAATTTCGGCAATAATCTTT	β-lactam	Antibiotic deactivation
185	blaVEB	CCCGATGCAAAGCGTTATG	GAAAGATTCCCTTTATCTATCTCAGACAA	β-lactam	Antibiotic deactivation
186	blaZ	GGAGATAAAGTAACAAATCCAGTTAGATATGA	TGCTTAATTTTCCATTTGCGATAAG	β-lactam	Antibiotic deactivation
187	cfxA	TCATTCCTCGTTCAAGTTTTCAGA	TGCAGCACCAAGAGGAGATGT	β-lactam	Antibiotic deactivation

188	cphA	GCGAGCTGCACAAGCTGAT	CGGCCCAGTCGCTCTTC	β-lactam	Antibiotic deactivation
189	fox5	GGTTTGCCGCTGCAGTTC	GCGGCCAGGTGACCAA	β-lactam	Antibiotic deactivation
190	Pbp5	GGCGAACTTCTAATTAATCCTATCCA	CGCCGATGACATTCTTCTTATCTT	β-lactam	Cellular protection
191	penA	AGACGGTAACGTATAACTTTTTGAAAGA	GCGTGTAGCCGGCAATG	β-lactam	Cellular protection
192	int1	GGCTTCGTGATGCCTGCTT	CATTCCTGGCCGTGGTTCT	MGE/Intrograse	Intrograse
193	intI1	CGAACGAGTGGCGGAGGGTG	TACCCGAGAGCTTGGCACCCA	MGE/Intrograse	Intrograse
194	tnpA, IS21 group	CATCATCGGACGGACAGAATT	GTCGGAGATGTGGGTGTAGAAAGT	MGE/Transposase	Transposase

195	tnpA, IS4	GGGCGGGTCGATTGAAA	GTGGGCGGGATCTGCTT	MGE/Transposase	Transposase
196	tnpA, IS6 group-01	AATTGATGCGGACGGCTTAA	TCACCAAACTGTTTATGGAGTCGTT	MGE/Transposase	Transposase
197	tnpA, IS6 group-02	CCGATCACGGAAAGCTCAAG	GGCTCGCATGACTTCGAATC	MGE/Transposase	Transposase
198	tnpA, IS6 group-03	GCCGCACTGTCGATTTTTATC	GCGGGATCTGCCACTTCTT	MGE/Transposase	Transposase
199	tnpA, IS6 group-04	TGCAGATGGTTTAACCTTGGATATTT	TCGGTTCATCAAACTGCTTCAC	MGE/Transposase	Transposase
200	tnpA, IS613 group	AGGTTCGGACTCAATGCAACA	TTCAGCACATACCGCCTTGAT	MGE/Transposase	Transposase
201	tnpA, ISEcp1B	GAAACCGATGCTACAATATCCAATTT	CAGCACCGTTTGCAGTGTAAG	MGE/Transposase	Transposase

202	tp614, IS4 family	GGAAATCAACGGCATCCAGTT	CATCCATGCGCTTTTGTCTCT	MGE/Transposase	Transposase

Table S4. Spearman's correlations between soil microbial antibiotic resistances estimated by percentage decrease of substrate induced respiration (SIR) and soil basal respiration (SBR) and the abundance and richness of antibiotic resistance genes (ARGs).

Percentage decrease	ARG	Spearman's correlation	
		R value	*P* value
SIR	Abundance	-0.503	*(0.047)
	Richness	-0.543	*(0.030)
SBR	Abundance	-0.729	**(0.001)
	Richness	-0.598	*(0.014)

*$P < 0.05$, and **$P < 0.01$. n=16.

Table S5. List of antibiotic resistance genes (ARGs) which were significantly different between nanoparticle treatments (nanoparticulate La_2O_3, Nd_2O_3, and Gd_2O_3) and control tested by one-way analysis of variance (ANOVA) in combination with *post hoc* least significant difference (LSD) test.

Number	ARG	ARG classification		ANOVA		LSD		
		Antibiotic resistance	Resistant mechanism	*F* value	*P* value	La100	Nd100	Gd100
1	tetE	Tetracycline	Efflux pump	5.315	*(0.015)	**(0.006)	NS(0.356)	NS(0.833)
2	tetR-02	Tetracycline	Efflux pump	4.747	*(0.021)	*(0.018)	NS(0.305)	NS(0.416)
3	tetT	Tetracycline	Cellular protection	5.821	*(0.011)	*(0.010)	NS(0.671)	NS(0.567)
4	blaTEM	β-lactam	Antibiotic deactivation	7.076	**(0.005)	*(0.026)	NS(0.127)	NS(0.239)
5	tetB-02	Tetracycline	Efflux pump	7.399	**(0.005)	*(0.012)	*(0.024)	NS(0.362)
6	tetG-01	Tetracycline	Efflux pump	10.806	***(0.001)	**(0.007)	***(0.000)	NS(0.656)
7	tetG-02	Tetracycline	Efflux pump	14.581	***(0.000)	***(0.000)	**(0.003)	NS(0.467)
8	vanTC-02	Vancomycin	Cellular protection	3.584	*(0.047)	*(0.048)	*(0.038)	NS(0.929)
9	acrA-04	Multidrug	Efflux pump	59.085	***(0.000)	NS(0.495)	***(0.000)	NS(0.422)

10	acrA-05	Multidrug	Efflux pump	4.079	*(0.033)	NS(0.595)	**(0.008)	NS(0.090)
11	yceL/mdtH-01	Multidrug	Efflux pump	3.526	*(0.049)	NS(0.505)	*(0.012)	NS(0.060)
12	tetQ	Tetracycline	Cellular protection	8.974	**(0.002)	NS(0.689)	**(0.003)	NS(0.427)
13	ampC/blaDHA	β-lactam	Antibiotic deactivation	4.680	*(0.022)	NS(0.640)	**(0.005)	NS(0.318)
14	vgb	MLSB	Antibiotic deactivation	5.137	*(0.016)	NS(0.989)	**(0.006)	NS(0.113)
15	ermB	MLSB	Cellular protection	7.764	**(0.004)	NS(1.000)	**(0.002)	NS(1.000)
16	vanRB	Vancomycin	Cellular protection	4.372	*(0.027)	NS(0.432)	*(0.011)	NS(0.818)
17	vanYD-01	Vancomycin	Cellular protection	11.363	***(0.001)	NS(0.459)	***(0.001)	NS(0.784)
18	mexF	Multidrug	Efflux pump	17.254	***(0.000)	NS(0.116)	***(0.001)	***(0.000)
19	oprD	Multidrug	Efflux pump	4.066	*(0.033)	NS(0.833)	*(0.040)	*(0.016)
20	oprJ	Multidrug	Efflux pump	7.075	**(0.005)	NS(0.881)	*(0.021)	**(0.004)
21	tetPB-02	Tetracycline	Cellular protection	3.520	*(0.049)	NS(0.294)	*(0.017)	*(0.021)
22	blaCTX-M-01	β-lactam	Antibiotic deactivation	17.317	***(0.000)	NS(0.997)	**(0.003)	***(0.000)
23	bla-L1	β-lactam	Antibiotic deactivation	4.893	*(0.019)	NS(0.061)	**(0.007)	**(0.005)

24	blaROB	β-lactam	Antibiotic deactivation	6.751	**(0.006)	NS(0.972)	*(0.046)	**(0.003)
25	pikR2	MLSB	Cellular protection	6.717	**(0.007)	NS(0.644)	**(0.005)	**(0.006)
26	acrR	Multidrug	Efflux pump	4.439	*(0.026)	NS(0.950)	NS(0.533)	**(0.008)
27	emrD	Multidrug	Efflux pump	3.961	*(0.036)	NS(0.969)	NS(0.242)	* (0.011)
28	marR	Multidrug	Efflux pump	18.641	***(0.000)	NS (1.000)	NS(0.546)	***(0.000)
29	mepA	Multidrug	Efflux pump	5.465	*(0.013)	NS(0.843)	NS(0.411)	**(0.004)
30	qacH-01	Multidrug	Efflux pump	12.210	***(0.001)	NS(0.782)	NS(0.223)	***(0.000)
31	aadA1	Aminoglycoside	Antibiotic deactivation	5.837	*(0.011)	NS(0.774)	NS(0.847)	**(0.004)
32	ampC-04	β-lactam	Antibiotic deactivation	4.040	*(0.034)	NS(0.520)	NS(0.077)	**(0.007)
33	blaOXY	β-lactam	Antibiotic deactivation	4.220	*(0.030)	NS(0.960)	NS(0.061)	*(0.014)
34	penA	β-lactam	Cellular protection	5.447	*(0.013)	NS(0.962)	NS(0.153)	**(0.004)
35	ereB	MLSB	Antibiotic deactivation	5.907	*(0.010)	NS(0.867)	NS(0.943)	** (0.004)
36	mphA-01	MLSB	Antibiotic deactivation	7.276	**(0.005)	NS(0.867)	NS(0.277)	**(0.001)
37	mphB	MLSB	Antibiotic deactivation	3.942	*(0.036)	NS(1.000)	NS(0.343)	*(0.012)

38	erm(34)	MLSB	Cellular protection	4.047	*(0.033)	NS(1.000)	NS(0.114)	*(0.013)
39	erm(36)	MLSB	Cellular protection	10.145	**(0.001)	NS(0.970)	NS(0.169)	***(0.000)
40	cmlA1-02	FCA	Efflux pump	4.104	*(0.032)	NS(0.909)	NS(0.084)	*(0.016)

La100, Nd100, and Gd100: high dose (100 mg kg^{-1}) of nano-La_2O_3, nano-Nd_2O_3, and nano-Gd_2O_3. MLSB: macrolide-lincosamide-streptogramin B resistance genes; FCA: fluoroquinolone, quinolone, florfenicol, chloramphenicol, and amphenicol resistance genes. *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$. n=4.

Table S6. List of antibiotic resistance genes (ARGs) groups categorized by antibiotic resistance tested by one-way analysis of variance (ANOVA) in combination with *post hoc* least significant difference (LSD) test.

Number	Antibiotic resistance	ANOVA		LSD		
		F value	*P* value	La100	Nd100	Gd100
1	Multidrug	17.077	***(0.000)	NS(0.298)	***(0.001)	***(0.000)
2	Aminoglycoside	0.898	NS(0.471)	NS(0.130)	NS(0.379)	NS(0.502)
3	Tetracycline	13.244	***(0.000)	***(0.001)	**(0.002)	NS(0.718)
4	β-lactam	4.730	*(0.021)	*(0.030)	NS(0.291)	NS(0.745)
5	MLSB	5.420	*(0.014)	*(0.049)	*(0.024)	**(0.002)
6	Vancomycin	5.624	*(0.012)	NS(0.072)	*(0.012)	NS(0.550)
7	FCA	1.547	NS(0.253)	NS(0.996)	NS(0.770)	NS(0.092)
8	Sulfonamide	1.114	NS(0.382)	NS(0.825)	NS(0.244)	NS(0.290)
9	Other	2.773	NS(0.087)	NS(0.910)	*(0.032)	NS(0.927)

La100, Nd100, and Gd100: high dose (100 mg kg^{-1}) of nano-La_2O_3, nano-Nd_2O_3, and nano-Gd_2O_3. MLSB: macrolide-lincosamide-streptogramin B resistance genes; FCA: fluoroquinolone, quinolone, florfenicol, chloramphenicol, and amphenicol resistance genes; Other: ARGs with unknown mechanism or conferring resistance to special antibiotics shown in Table S3. *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$. n=4.

Figure legends

Fig. S1 Transmission electron microscope images of the nanoparticles used in this study. Nanoparticles were suspended in deionized H_2O.

Fig. S2 Time-course effects of nanoparticle dose on antibiotic resistance reflected by microbial biomass in fluvo-aquic soil (Inceptisol) and red soil (Ultisol). The antibiotic resistance in microbial community was determined by the percentage decrease of substrate induced respiration (SIR) after additional tetracycline exposure. a-e, Nano-La_2O_3 exposure; f-j, Nano-Nd_2O_3 exposure; k-o, Nano-Gd_2O_3 exposure. The time-course was shown as 0 d, 1 d, 7 d, 30 d, and 60 d from left to right. Error bars indicate the standard deviation of four independent replicates.

Fig. S3 Time-course effects of nanoparticle dose on antibiotic resistance reflected by microbial activity in fluvo-aquic soil (Inceptisol) and red soil (Ultisol). The antibiotic resistance in microbial community was determined by the percentage decrease of soil basal respiration (SBR) after additional tetracycline exposure. a-e, Nano-La_2O_3 exposure; f-j, Nano-Nd_2O_3 exposure; k-o, Nano-Gd_2O_3 exposure. The time-course was shown as 0 d, 1 d, 7 d, 30 d, and 60 d from left to right. Error bars indicate the standard deviation of four independent replicates.

Fig. S1

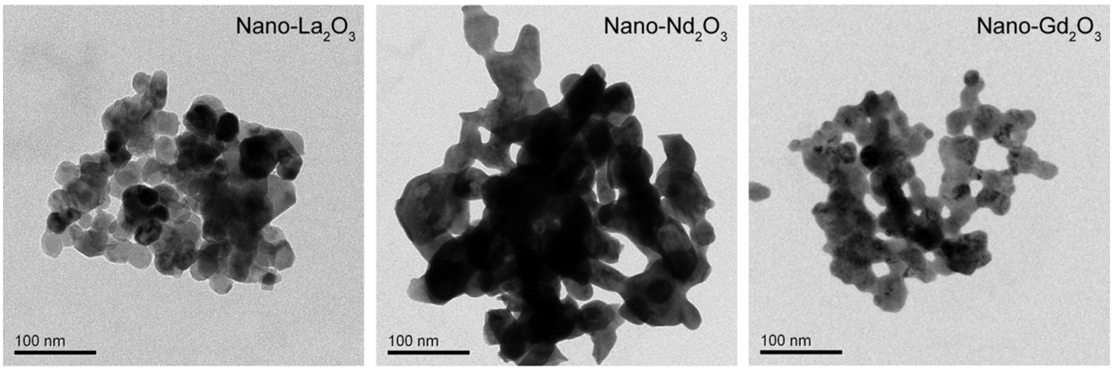
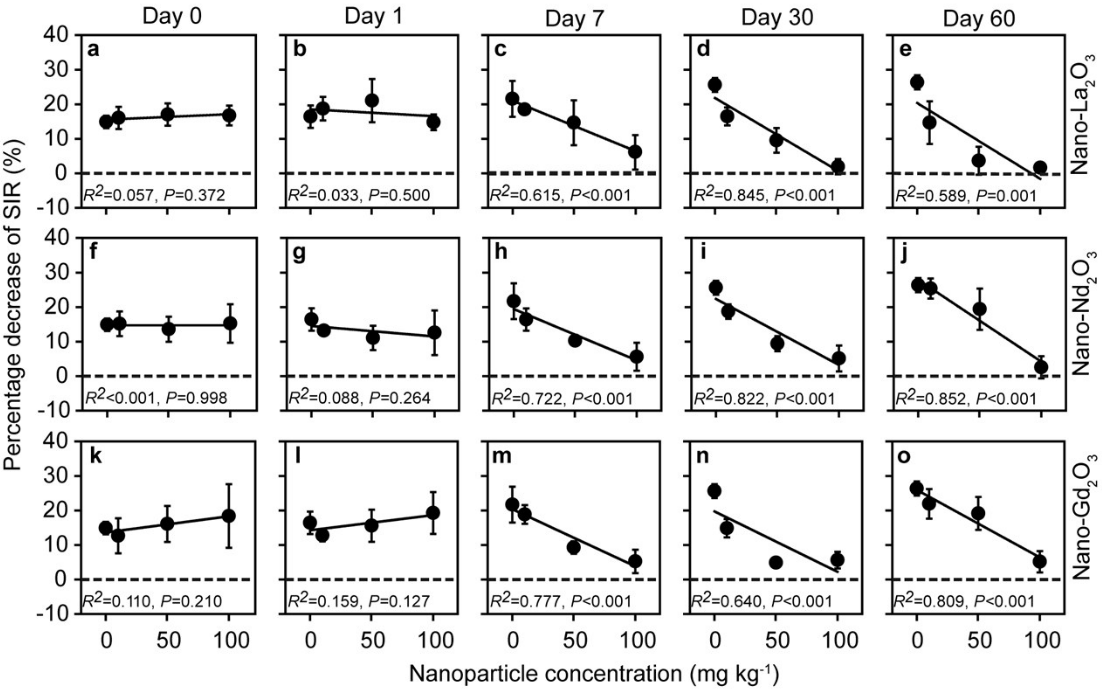


Fig. S2

Fluvo-aquic soil (Inceptisol)



Red soil (Ultisol)

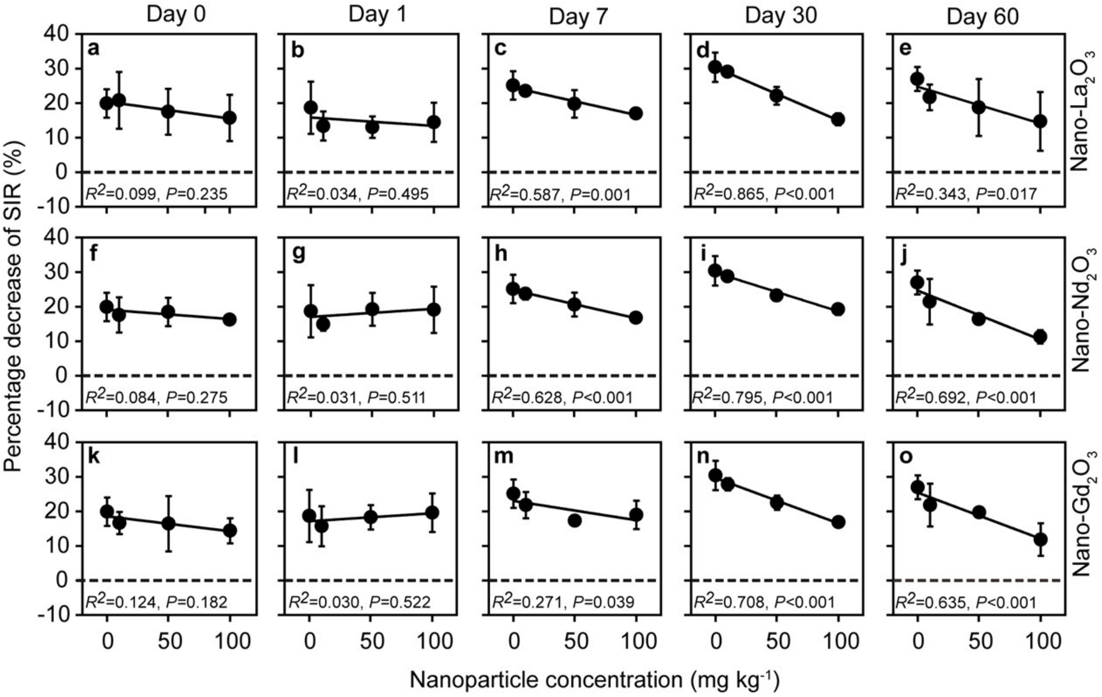
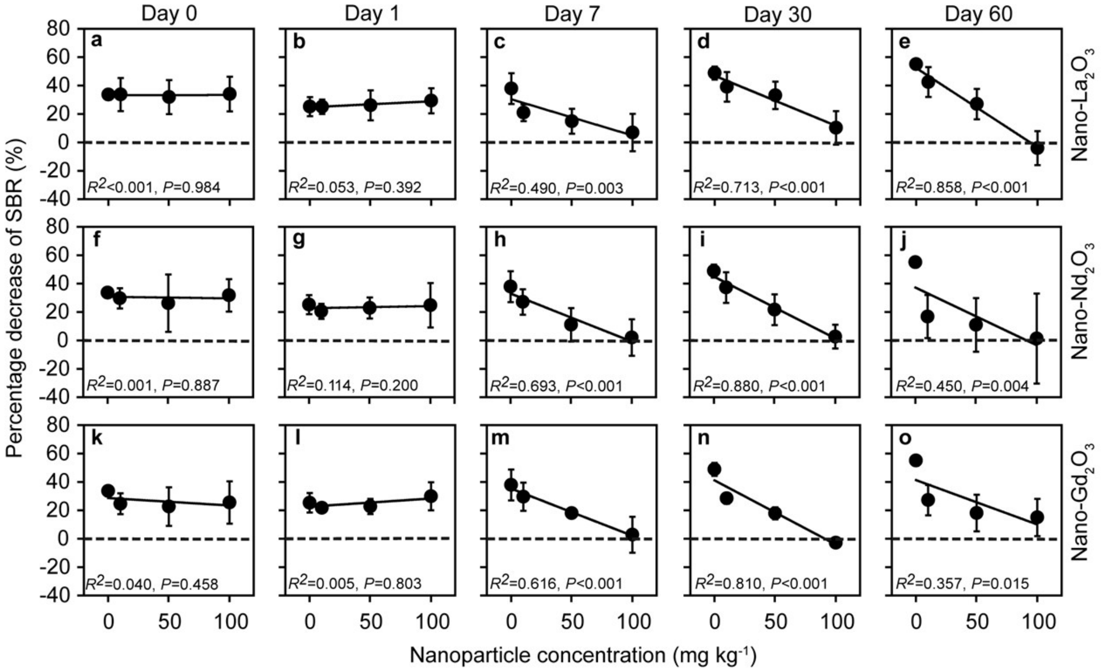


Fig. S3

Fluvo-aquic soil (Inceptisol)



Red soil (Ultisol)