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1 **Does ochre have the potential to be a remedial treatment for As-contaminated soils?**

2

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4

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12

13 **Abstract**

14 Ochre is an iron oxyhydroxide-rich waste that accumulates in water bodies associated with
15 disused mines. Laboratory experiments were conducted to examine the potential of four
16 different ochres to be used as remedial agents for As contaminated soils. The ochres
17 removed As from solution (200 and 500 mg L⁻¹) in adsorption experiments at pH 3 and 8 and
18 when added to As contaminated soil (5 % w/w) significantly reduced As release to solution.
19 In both these experiments the highest surface area ochres performed best. The impact of
20 ochre amendments on uptake of As from soil by plants and humans and release of As to
21 ground water was assessed in a year-long incubation. Ochres increased soil pH and
22 reduced CaCl₂ extractable As but had no consistent effect on plant growth, plant As uptake
23 or As extraction in physiologically based extraction tests. Ochre may be better used for water
24 treatment than soil remediation.

25 **Keywords:** arsenic; ochre; contaminated soil; incubation; bioassays

26

27 **Capsule:** Ochre amendments to As-contaminated soil increase pH and reduce CaCl₂
28 extractable As but have no impact on plant growth, As uptake or PBET extractable As.

29

30 **Introduction**

31 High concentrations of As in soils and water bodies occur throughout the world due to
32 anthropogenic activities such as mining, smelting and wood preservative usage (Abrahams
33 and Thornton; Álvarez-Ayuso et al., 2012; Eapaea et al., 2007; Lin et al., 2004; Mench and
34 Bes, 2009; Nriagu et al., 2007; Ritchie et al., 2013; Warren et al., 2003). The main routes of
35 arsenic poisoning from contaminated soils are accidental ingestion or inhalation of
36 contaminated soil or water or consumption of plants grown on As-contaminated soils
37 (Miretzky and Cirelli, 2010). There is a need for affordable remedial solutions that can be
38 applied to As-contaminated soil. It is increasingly recognised that the remedial methods of
39 disposal or isolation of contaminated soil are not sustainable. This had led to a growing
40 willingness to use organic or mineral amendments to alter soil chemistry and break
41 pathways between pollutant sources and receptors (e.g. Hodson, 2010; Jones and Healey,
42 2010; O'Day and Vlassopoulos, 2010).

43

44 A large literature reports the sorption of many potential contaminants to Fe oxides, e.g.
45 Cornell and Schwertmann, 2003 and references therein, Jambor and Dutrizac, 1998 and
46 references therein. Much work has investigated As adsorption by Fe oxides (e.g. Bowell,
47 1994; Matis et al., 1997; Sun and Doner, 1998; Jain et al., 1999; Garcia-Sanchez et al., 2002;
48 Goldberg, 2002; Ford, 2002; Jackson and Miller, 2000; Grafe et al., 2001; Waltham and Eick,
49 2002; Sun and Doner, 1996; Manning et al., 1998; Goldberg and Johnston, 2001; Livesey
50 and Huang, 1981; Elkhatib et al., 1984a,b; Manning and Suarez, 2000; Smith et al., 2002)
51 and this had led to investigations into using Fe oxides to remediate As-contaminated soil

52 (e.g. Boisson et al., 1999; Garcia-Sanchez et al., 1999; Warren et al., 2003; Warren and
53 Alloway, 2003; Nielsen et al., 2011; Kumpiene et al., 2008; Lee et al., 2011). Ochre is the
54 name given to Fe(III) oxyhydroxide precipitates that accumulate in the outflows of mine
55 systems. In the United Kingdom the Coal Authority is responsible for over 68 (as of August
56 2014) mine water treatment schemes that remove c. 4000 tonnes of iron per year from water
57 courses resulting in ochre production (UK Government, 2014). Some of this ochre is used in
58 brick production to partially offset the waste management costs (Clean Rivers Trust, 2012).
59 Additionally, research has been carried out, with mixed success, into using ochre to limit
60 phosphate concentrations in water and soil (Fenton et al., 2012; Heal et al., 2005; Dobbie et
61 al. 2009; Sibrell et al. 2009). However, there is still no mature market for ochre in the UK; its
62 accumulation poses a waste disposal problem.

63

64 Previously (Doi et al., 2005) we showed that ochre may be an appropriate remedial
65 amendment. However, properties of ochres are site specific. Here we characterise a further
66 4 ochres to further demonstrate the ability of ochres to adsorb As. We then report a year
67 long incubation study investigating whether ochre amendments can break the most
68 significant pathways (leaching to ground water, ingestion of soil, uptake by plants) between
69 As-contaminated soil and receptors. We also examine the impact on ochre amendment on
70 soil microbial functioning via assay of hydrolytic enzyme activity.

71

72 **Materials and methods**

73 As-bearing soils were collected from the upper 20 cm of profiles located at a former mine
74 site (Devon Great Consols, SX 72878 96419, soil DGC), a former As calciner (Tresavean,
75 Lanner, Redruth, SW 72423 39743, soils RRT1, RRT2) and an allotment site (Scunthorpe,
76 SE 89344 10835, soil SCP). Soils were air-dried, sieved to ≤ 2 mm and stored prior to
77 characterisation and use in experiments.

78

79 Four ochres were provided by the UK Coal Authority: Bull House (SE 421192 402506, BH)
80 and Woolley (SE 41586 78838, WY) from passive treatment works, Old Meadows from an
81 active treatment works (SJ 43496 95991, OM) and Six Bells from a combined passive and
82 active treatment works (SO 22250 03039, SB). All ochres were supplied moist in sealed,
83 plastic containers and were air-dried and crushed to ≤ 2 mm prior to use in experiments.

84

85 pH (ISO, 2005), loss on ignition (for organic matter content, Rowell, 1994), particle size
86 distribution, BET surface area (de Boer et al., 1987), total As and Fe by aqua regia digest,
87 acid ammonium oxalate and citrate-bicarbonate-dithionite extractable Fe (Loeppert and
88 Inskeep, 1996), point of zero charge (Zelazny et al., 1996) and mineralogy by X-ray
89 diffraction were determined following standard established methods (details in
90 Supplementary material).

91

92 In adsorption experiments to investigate sorption of As by ochres 0.1g ochrewas added to
93 0.1 M sodium nitrate (40 mL); pH was adjusted to 3 or 8 using 0.1 M NaOH or 0.1M HCl.
94 The mixture was shaken on an end-over-end shaker at 20 ± 1 °C for 24 hours in darkness
95 then 40 μ L of 200 or 500 mg L⁻¹ NaAsO₃ solution was added; pH was readjusted to pH 3 or 8
96 using NaOH or HCl and the mixtures were returned to the shaker. 15 replicates of each
97 ochre-As combination were used and 15 ochre-free controls. After 0.5, 1, 3, 6 and 24 hours,
98 three sacrificial replicates were removed, pH adjusted back to 3 or 8, samples were
99 centrifuged at 2113 g for 15 minutes and the centrifugate filtered through Whatman no. 2
100 filter papers. Arsenic concentrations were determined using ICP-OES.

101

102 In batch experiments to investigate reduction of As release from contaminated-soil into
103 solution due to ochre addition 1g As-contaminated soil was mixed with ochre (0.05, 0.1, 0.2

104 and 0.5 g) and added to 0.01 M CaCl₂ solution (20 mL). The mixture was shaken on an end-
105 over-end shaker at 20 ± 1 °C for 24 hours in darkness then centrifuged at 2113 g for 10
106 minutes. The supernatant was filtered (Whatman no. 2) and analysed for As by ICP-OES
107 and pH.

108

109 Incubation experiments investigated the impact of ochre amendments on As mobility under
110 pseudo-field conditions. Ochre (60 g) was added to soil (1200 g) (DGC, RRT2). Treatments
111 and controls were moistened to 100 % water holding capacity and incubated at 30 °C in
112 sealed plastic bags for 52 weeks in darkness. The soil was mixed weekly. Five replicates
113 were established per treatment and subsamples taken after 3, 12, 24 and 52 weeks of
114 incubation for analysis. As Fe and As are redox sensitive elements we measured Eh at
115 weeks 24 and 52 (there being insufficient resource to measure it at the other sampling
116 points) in addition to pH (ISO, 2005) at each sampling point to determine potential changes
117 in Fe and As speciation. Acid ammonium oxalate and citrate-bicarbonate-dithionite
118 extractable Fe and a fluorescein diacetate (FDA) hydrolysis assay to measure microbial
119 activity following the method of Adam and Duncan (2001) (Supplementary materials) were
120 carried out on the subsamples.

121

122 We assessed the effect of ochre amendments on the most likely pathways for As
123 contamination in soils to impact on the environment and human health. To determine
124 possible As leaching into ground water 1 g of air-dried soil was added to 20 mL of 0.01M
125 CaCl₂ solution (to represent soil solution; Houba et al., 1990) and shaken on an end-over-
126 end shaker for 24 hours at 20 °C. Samples were centrifuged at 2113 g for 15 minutes at 20
127 °C. Supernatant pH was measured.. The supernatant was filtered (Whatman No 2) and
128 analysed for As by ICP-OES. In a plant growth and As uptake bioassay , rye grass (*Lolium*
129 *perenne* . L., 0.5 g seeds per pot) was grown in 150g of incubated soil in a plant growth
130 room for 40 days. Plants were harvested and shoots cut 1 cm above ground level; roots

131 were washed in deionised water to remove attached soil. Samples were dried at 70 °C to a
132 constant mass, digested in nitric acid and analysed for As by ICP-OES. For week 3 and 52
133 subsamples, a PBET extraction to assess As availability to humans on ingestion of the soil
134 (Intawongse and Dean, 2008) was carried out. Air dried, $\leq 250 \mu\text{m}$ soil (1g) was shaken with
135 simulated stomach and intestine fluids which were analysed for As by ICP-OES. Analytical
136 and methodological details are given in the Supplementary materials.

137

138 **Quality control and statistical analysis**

139 An in-house 500 ppb reference solution was analysed by ICP-OES at the start of each
140 analytical run and returned values within 10% of established concentrations. The detection
141 limit for the adsorption and batch experiment As solutions and CaCl_2 extractions was $8 \mu\text{g L}^{-1}$
142 calculated from the mean plus 6 times the standard deviation on ten replicate analyses of
143 the blank calibration standard (Gill, 1997). Detection limits were $1.133 \pm 0.198 \text{ mg kg}^{-1}$ for
144 plant digests and 61.6 mg kg^{-1} and $121.95 \text{ mg kg}^{-1}$ for the stomach and small intestine phase
145 of the PBET analysis. Method blanks were run for all extractions and results were blank
146 corrected where appropriate. For aqua regia digests an in-house reference material (SS39)
147 traceable to CRM 143R sewage sludge-amended soil (Commission of European
148 Communities Community Bureau of Reference BCR) was digested. Recoveries were 95 –
149 105 % for As. For plant digests an in-house reference material (Hay 2) was digested with
150 each batch of digests. Recoveries were 98 – 102 %. Analytical precision for the different
151 matrices by duplicate analysis of 10 % of the samples (Gill, 1997) was $> 95\%$.

152

153 Statistical analysis was carried out using SigmaStat 12.0.

154

155 **Results and discussion**

156 The soils and ochres showed a range of properties (Table 1). The ochres contained
157 relatively low concentrations of As, had a range of surface areas and the crystalline material
158 present was goethite.

Table 1. Mean soil and ochre properties used in the adsorption and batch experiments (n = 3 ± standard deviation)

Parameter	Soil					Ochre				
	DGC	RRT1	RRT2	SCP		BH	OM	SB	WY	
pH	3.74 ^a ± 0.06	4.70 ^{ab} ± 0.05	5.26 ^{ab} ± 0.04	7.27 ^b ± 0.09	NP	5.63 ^a ± 0.07	7.16 ^{ab} ± 0.11	6.65 ^{ab} ± 0.13	7.48 ^b ± 0.08	NP
LOI / %	4.18 ^a ± 0.12	7.52 ^b ± 0.02	4.65 ^c ± 0.24	8.14 ^d ± 0.19	P	11.15 ^a ± 0.18	9.95 ^b ± 0.75	12.46 ^c ± 0.08	13.67 ^d ± 0.39	P
Clay / %	1.31 ^a ± 0.09	3.19 ^{ab} ± 0.16	1.94 ^{ab} ± 0.10	5.09 ^b ± 0.44	NP	22.8 ^a ± 7.17	22.00 ^a ± 1.11	10.74 ^b ± 2.26	15.10 ^{ab} ± 1.87	P
Silt / %	9.78 ^a ± 0.63	32.57 ^{ab} ± 2.76	15.00 ^{ab} ± 0.61	39.93 ^b ± 1.94	P	45.63 ^a ± 7.82	54.47 ^{ab} ± 3.84	26.40 ^c ± 3.56	64.87 ^b ± 3.62	P
Sand / %	88.93 ^a ± 0.74	64.23 ^b ± 2.87	83.07 ^c ± 0.67	54.97 ^d ± 2.12	P	31.57 ^a ± 15.00	23.57 ^a ± 4.92	62.80 ^b ± 5.80	20.03 ^a ± 5.47	P
Textural class	Sand	Sandy loam	Loamy sand	Sandy loam		Loam	Silt loam	Sandy loam	Silt loam	
Total As / mg kg ⁻¹	33200 ^a ± 3020	310 ^{ab} ± 29.5	1810 ^{ab} ± 47.6	124 ^b ± 9.15	NP	2.03 ^a ± 0.07	< 0.02 ^b	4.24 ^c ± 0.05	< 0.02 ^b	P
Total Fe / %	11.2 ^a ± 0.31	2.67 ^b ± 0.09	3.36 ^c ± 0.15	13.0 ^d ± 0.17	P	60.57 ^a ± 0.31	47.20 ^b ± 1.23	59.87 ^{ab} ± 3.26	57.41 ^{ab} ± 0.42	NP
AO Fe / %	ND	ND	ND	ND		12.84 ^a ± 0.43	24.19 ^b ± 0.54	25.25 ^b ± 0.61	25.00 ^b ± 0.35	P
CBD Fe / %	ND	ND	ND	ND		94.21 ^{ab} ± 1.20	79.28 ^b ± 0.78	96.15 ^a ± 1.46	83.23 ^{ab} ± 17.43	NP
PZNC	ND	ND	ND	ND		5.36 ^a ± 0.29	6.15 ^a ± 0.20	5.94 ^a ± 0.46	4.26 ^a ± 0.31	NP
BET / m ² g ⁻¹	ND	ND	ND	ND		170 ^a ± 5.70	261 ^b ± 1.71	65.4 ^c ± 0.72	79.9 ^d ± 0.50	P
Mineralogy / %										
Goethite	BDL	BDL	BDL	16		100	100	100	100	
Quartz	43	70	65	84		BDL	BDL	BDL	BDL	
Chlorite + kaolinite	45	7	11	BDL		BDL	BDL	BDL	BDL	
Mica	6	11	13	BDL		BDL	BDL	BDL	BDL	
Microcline	BDL	7	9	BDL		BDL	BDL	BDL	BDL	
Fluorite	5	1	1	BDL		BDL	BDL	BDL	BDL	
Albite	Trace	4	1	BDL		BDL	BDL	BDL	BDL	
Siderite	1	Trace	Trace	BDL		BDL	BDL	BDL	BDL	

AO = ammonium oxalate extractable Fe; CBD = citrate bicarbonate dithionite extractable Fe; ND = not determined; PZNC = point of net zero charge; BDL = below detection limit of ~ 5 %. Across the soils and across ochres, values were compared by Analysis of Variance (ANOVA) if normally distributed (P) or Kruskal-Wallis Analysis of Variance on Ranks if not normally distributed (NP), values with different subscripts are significantly different ($p \leq 0.05$; Tukey test).

1 **Adsorption experiments**

2 Since Fe oxides can adsorb As (Dixit and Hering, 2003; Kanematsu et al., 2013; Miretzky
3 and Cirelli, 2010) it was expected that the ochres would sorb As and this was verified in
4 initial adsorption experiments conducted at pHs above and below the PZNC (Fig. 1). The
5 majority of adsorption happened within the first 30 minutes of the experiment (Fig. 1), as in
6 other experiments using ochres (Doi et al., 2005). The ochre PZNC values (Table 1) are
7 lower than reported literature values of 7.5 – 9.0 for goethite (Stumm and Morgan, 1981;
8 Bigham et al., 2002). This is probably due to organic matter in the ochres (Appel et al. 2003).
9 Significant adsorption occurred at both pH 3 and 8, below and above the PZNC, suggesting
10 that sorption was dominated by chemisorption rather than electrostatic interactions.
11 Consistent with other anion adsorption studies, adsorption was generally greater at pH 3
12 than pH 8 (Giménez et al., 2007; Dixit and Hering, 2003; Matis et al., 1997). 3-way analysis
13 of variance (ANOVA) indicated that at initial As concentrations of 200 and 500 mg L⁻¹ there
14 were significant interactions between ochre type, pH and duration of experiment ($p \leq 0.01$)
15 (Tables S1 and S2). Generally there was little change in adsorption between 6 and 24 hours.
16 Considering the 24 hour data, 3-way ANOVA indicated a significant interaction between
17 ochre type, pH and initial As concentration ($p \leq 0.01$) (Table S3). At pH 3 and 8 there were
18 significant differences between the adsorption that occurred on BH and OM between the
19 initial As concentrations of 200 and 500 mg L⁻¹; more adsorption occurred for initial As
20 concentrations of 500 mg L⁻¹ for BH but less for OM. The greatest adsorption, at both 200
21 and 500 mg L⁻¹ As was shown by OM which had the highest surface area; SB and WY
22 showed the least adsorption and had the lowest surface areas. Thus it seems likely that
23 differences in adsorption between the ochres were primarily driven by surface area and
24 therefore availability of adsorption sites.

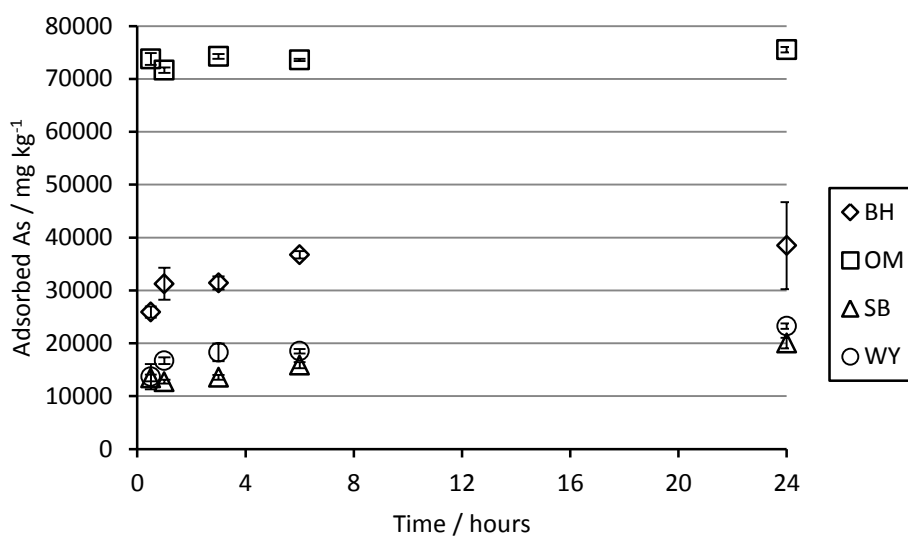
25

26

27 **Fig. 1.** Arsenic adsorption by the four different ochres (BH, OM, SB and WY) at a) pH 3,
 28 initial As concentration of 200 mg L⁻¹, b) pH 3, initial As concentration of 500 mg L⁻¹, c) pH 8,
 29 initial As concentration of 200 mg L⁻¹, d) pH 8, initial As concentration of 500 mg L⁻¹.
 30 Adsorption values are means of 3 replicate analyses, vertical error bars are standard
 31 deviations.

32

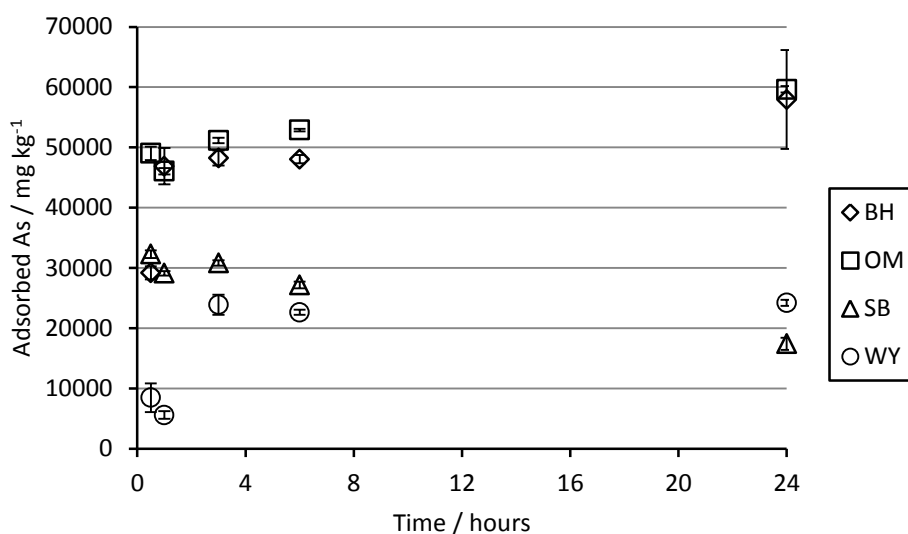
33 a) pH 3, 200 mg/L As



34

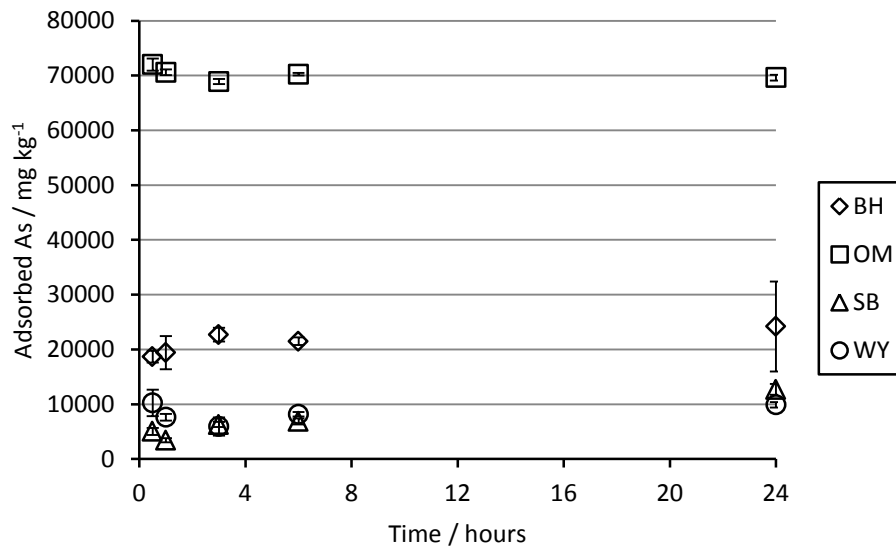
35

36 b) pH 3, 500 mg / L As



37

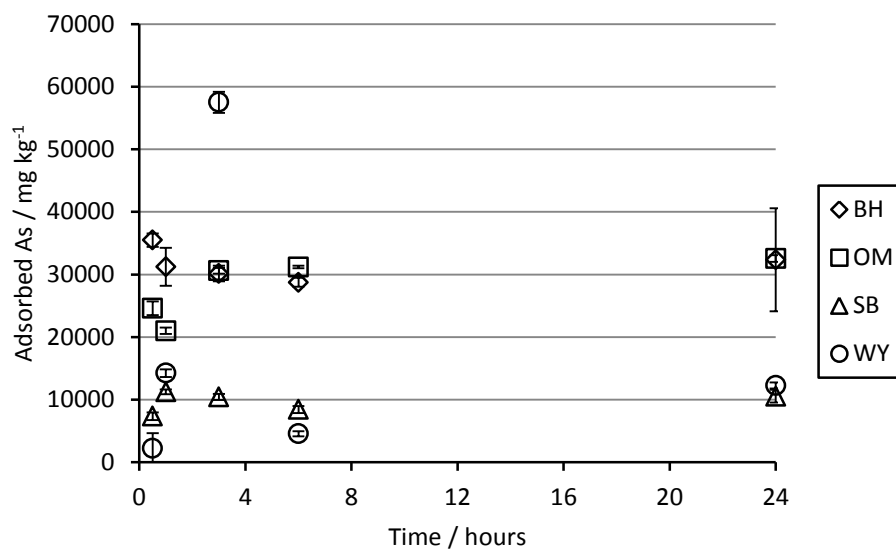
38 c) pH 8, 200 mg/L As



39

40

41 d) pH 8, 500 mg / L As



42

43

44 **Batch experiments**

45 Arsenic concentrations in batch experiments using RRT1 and SCP soils were below

46 detection ($8 \mu\text{g L}^{-1}$) and are not discussed further. Unamended RRT2 soil released less As

47 into solution than DGC (Fig. 2) though as a proportion of total As, RRT2 released more,
48 highlighting the importance of determining mobile or available contaminant concentrations
49 rather than total concentrations in pollution studies and risk assessment. Addition of even a
50 small amount of ochre reduced As release into solution. The decrease in As release with
51 increasing ochre addition was presumably due to provision of more sorption sites (Fig. 2).
52 Arsenic concentration in solution was below detection in the RRT2 experiment at all levels of
53 ochre addition.

54

55 Two-way ANOVA of the DGC data indicates a statistically significant effect of both ochre
56 type and mass of ochre added on As concentration in solution and a significant interaction
57 between the two ($p \leq 0.001$) (Table S4). OM and WY remove significantly more As from
58 solution than BH and SB at ochre loadings of 0.05 and 0.1 g ($p \leq 0.01$) but at the higher
59 loadings effects of the different ochres are not significantly different. Perhaps at these
60 masses of ochre, adsorption sites are not a limiting factor for As removal. Increasing ochre
61 loadings does not increase As removal from solution by OM and WY but has a significant
62 effect on As removal for BH and SB. OM has a higher surface area than the other ochres
63 (Table 1) and was the most adsorptive in the adsorption experiments. However, WY has a
64 relatively low surface area and, in adsorption experiments showed relatively low adsorption,
65 together with BH. This suggests that interaction with the soil played an important role in
66 determining the level of As removal. The OM and WY suspensions both had higher pHs
67 (Table S5) than the BH and SB suspensions but it seems unlikely that higher pH causes
68 reduced As release since typically As adsorption is greater at lower pH, as observed in our
69 adsorption experiments and elsewhere (Giménez et al., 2007; Dixit and Hering, 2003; Matis
70 et al., 1997).

71

72 The adsorption and batch experiments demonstrate that ochres adsorb As and therefore
73 have the potential to be used to remediate As-contaminated soils. However, in both cases,

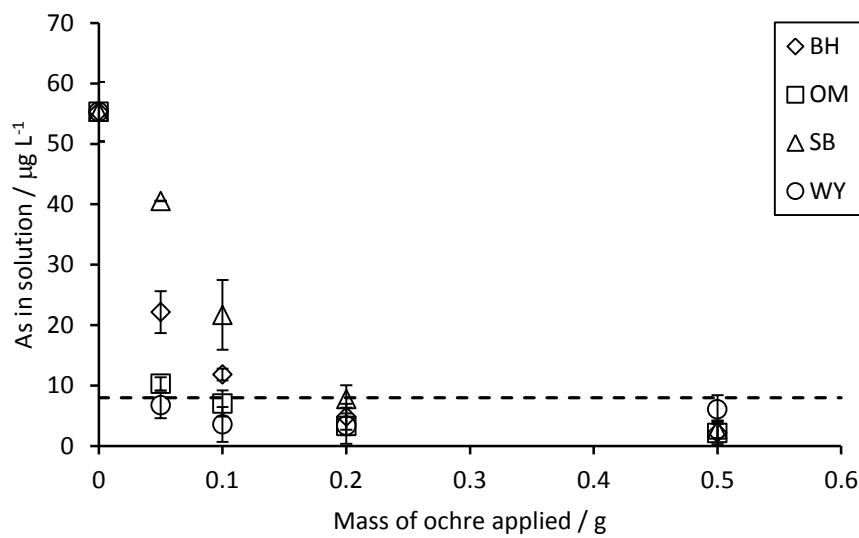
74 there was a high ratio of solution to solid, maximising interaction between As in solution and
75 potential sorbing surfaces. If mineral amendments are to be used in the field they will be
76 mixed with soils and the level of contaminant – mineral interaction will be less. Therefore
77 further experiments, with more realistic ochre – soil mixtures are necessary to fully assess
78 the merits of mineral amendments for soil remediation.

79

80 **Fig. 2.** Arsenic concentration in solution after 24 hour batch experiment solutions using 1 g
 81 of As-bearing soil and varying masses of ochre for a) DGC soil and b) RRT2 soil. Values are
 82 mean of three replicates, error bars are standard deviations. The dashed horizontal line
 83 indicates the detection level of $8 \mu\text{g L}^{-1}$.

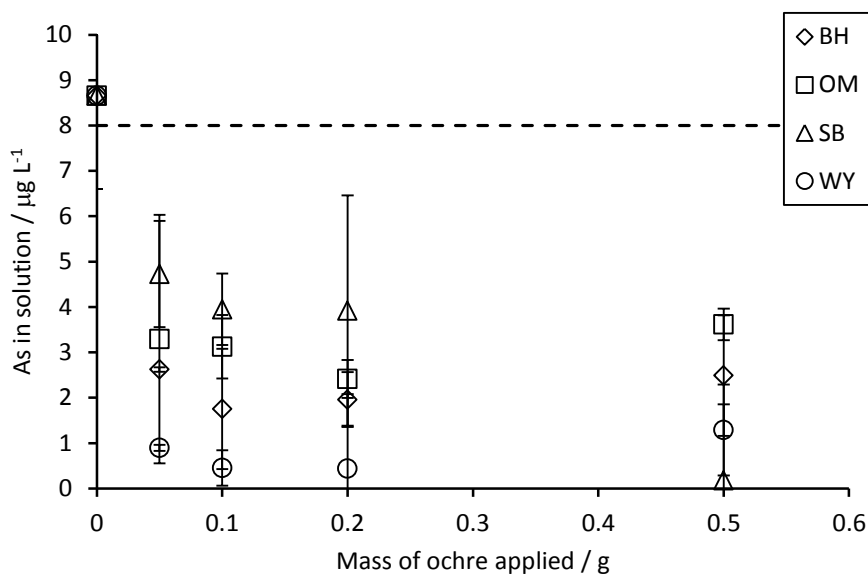
84

85 a) DGC soil



86

87 b) RRT2 soil



88

89 **Incubation experiments**

90 Ochre amendments reduced the amount of 0.01 M CaCl₂ extractable As (Table 2a, S6). For
 91 RRT2 soil the amendments reduced extractable As from 0.27 ± 0.08 mg kg⁻¹ to below
 92 detection (8 µg L⁻¹, 0.16 mg kg⁻¹). For DGC soil, similar to the adsorption and batch
 93 experiments, OM ochre had the most significant impact. Extractable As increased over time
 94 for the unamended and amended DGC soil (p ≤ 0.01). However, the ratio of extractable As in
 95 the unamended to ochre amended soils (Table 2b) either remained the same or increased
 96 (p ≤ 0.01) suggesting that the efficacy of ochre treatments in reducing As mobility was
 97 constant or increased with respect to incubation time.

98

99 Table 2a. 0.01 M CaCl₂ extractable As in the DGC soils.

Ochre	Week 3	Week 12	Week 24	Week 52
None	2.25 ± 0.41 aA	3.85 ± 0.33 aB	6.27 ± 0.33 aC	6.4 ± 0.30 aC
BH	1.69 ± 0.07 bcA	3.44 ± 0.28 bB	5.02 ± 0.19 bC	4.38 ± 0.16 bD
OM	0.79 ± 0.04 dA	1.33 ± 0.08 cB	1.41 ± 0.11 cB	2.01 ± 0.09 cC
SB	1.82 ± 0.11 bA	3.26 ± 0.13 bB	4.21 ± 0.21 dC	3.47 ± 0.24 dB
WY	1.45 ± 0.26 cA	2.65 ± 0.18 dB	2.79 ± 0.09 eB	5.25 ± 0.08 eC

100 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 101 different (p ≤ 0.05, Holm-Sidak method). Lower case letters are for comparisons within
 102 specific weeks, capital letters within specific ochre treatments.

103

104 Table 2b. Ratio of 0.01 M CaCl₂ extractable As in the unamended to amended DGC soils.

	Week 3	Week 12	Week 24	Week 52
None / BH	1.33 ± 0.06 ab	1.12 ± 0.02 a	1.25 ± 0.01 a	1.46 ± 0.01 a
None / OM	2.85 ± 0.29 a	2.90 ± 0.09 a	4.44 ± 0.17 b	3.18 ± 0.04 b
None / SB	1.24 ± 0.06 ab	1.18 ± 0.01 a	1.49 ± 0.01 c	1.84 ± 0.02 c
None / WY	1.56 ± 0.16 ab	1.45 ± 0.03 a	2.25 ± 0.02 d	1.22 ± 0.00 a

105 Uncertainties in ratios are propagated through the calculations from the standard deviations
 106 about mean As extraction. Ratios are compared using Least squared difference. Same
 107 letters = treatment not significantly different between weeks

108

109 Addition of ochre amendments typically increased pH in both soils (Tables 3, S7) though
 110 there are no consistent trends in pH change over time. pH increases due to ochre addition

111 have been observed previously (Doi et al., 2005; Nielsen et al., 2011). Doi et al. (2005)
 112 attributed the increases to dissolution of calcite present as an impurity in the ochres. No
 113 calcite was detected in the present ochres but the ochre pH (Table 1) suggests that calcite
 114 might be present, buffering pH, at concentrations below the XRD level of detection (c. 5%).
 115 Alternatively the pH increase may be due to the release of OH⁻ due to sorption of anionic As
 116 species to the ochre (Jain et al., 1999).

117

118 Table 3. pH of a) DGC and b) RRT2 soil.

Ochre	Week 3	Week 12	Week 24	Week 52
None	2.82 ± 0.02 aA	2.56 ± 0.11 aB	2.90 ± 0.03 aC	2.96 ± 0.03 aD
BH	2.79 ± 0.02 aA	2.58 ± 0.07 aB	2.88 ± 0.03 aC	2.97 ± 0.02 aD
OM	3.58 ± 0.09 bA	3.30 ± 0.04 cB	3.39 ± 0.02 bC	3.33 ± 0.02 bB
SB	2.91 ± 0.02 cA	2.79 ± 0.03 dA	2.96 ± 0.02 cAB	3.00 ± 0.03 aB
WY	3.38 ± 0.03 dA	3.25 ± 0.03 cB	3.30 ± 0.02 dAC	3.26 ± 0.03 cC

119 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 120 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 121 specific weeks, capital letters within specific ochre treatments.

122

123 Table 3b.

Ochre	Week 3	Week 12	Week 24	Week 52
None	4.28 ± 0.09 aA	4.05 ± 0.13 aB	4.54 ± 0.09 aC	4.55 ± 0.04 aC
BH	4.45 ± 0.13 bA	4.44 ± 0.10 bA	4.77 ± 0.07 bB	4.70 ± 0.04 bB
OM	5.12 ± 0.10 cAB	5.02 ± 0.06 cA	5.23 ± 0.04 cB	5.16 ± 0.04 cB
SB	4.60 ± 0.05 dAB	4.58 ± 0.07 dA	4.71 ± 0.05 bB	4.65 ± 0.03 bAB
WY	5.08 ± 0.06 cAB	4.92 ± 0.04 eC	5.13 ± 0.04 cA	5.02 ± 0.01 dBC

124 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 125 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 126 specific weeks, capital letters within specific ochre treatments.

127

128 Eh was positive at weeks 24 and 52 in the incubation experiment (Table 4, S8). For DGC
 129 soil there were slight differences between treatments and, when significant changes
 130 occurred between 24 and 52 weeks Eh became more oxidising. Only in week 52 did one
 131 treatment (WY) result in a lower Eh than the unamended soil. In contrast there was a
 132 significant decrease in Eh between weeks 24 and 52 for all the RRT2 treatments. The Eh-pH
 133 conditions recorded fall around the Fe²⁺_(aq) - FeOOH and H₃AsO₃ (i.e. As^{III}) - H₂AsO₄⁻ (i.e.

134 As^V) stability field divides in Eh-pH diagrams (e.g. Scheffer and Schachtschabel, 1989; Lu
 135 and Zhu, 2011) making it hard to be certain of the speciation of either the Fe or As in the
 136 systems or the stability of the ochres. The ochres may have undergone reductive dissolution
 137 during the experiment. At the start of the experiment As may have been present as As^V in
 138 the soil with the reduction in Eh in the RRT2- OM, SB and WY mixtures causing reduction to
 139 As^{III}. The reduction in Eh could be driven by oxidation of organic matter. RRT2 contains
 140 slightly more organic matter than DGC which may explain why no Eh reductions were seen
 141 in the DGC mixes. However, if the Eh reduction is due to organic matter oxidation it is not
 142 clear why this occurred in the RRT2- OM, SB and WY mixtures but not the RRT2-BH mixture
 143 or untreated soil.

144

145 Table 4. Eh of a) DGC and b) RRT2 soil (mV).

Ochre	Week 24	Week 52
None	438.2 ± 28.0 abA	506.0 ± 8.8 aB
BH	418.2 ± 19.9 abA	454.4 ± 47.8 abA
OM	383.4 ± 28.5 aA	484.6 ± 17.7 abB
SB	453.4 ± 41.7 bA	469.8 ± 10.6 abA
WY	433.4 ± 53.9 abA	439.6 ± 14.1 bA

146 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 147 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 148 specific weeks, capital letters within specific ochre treatments.

149

150 Table 4b.

Ochre	Week 24	Week 52
None	439.6 ± 49.7 aA	476 ± 9.6 aA
BH	474.2 ± 42.6 aA	397.6 ± 54.5 bB
OM	469.0 ± 25.8 aA	204.0 ± 34.0 cB
SB	471.2 ± 30.4 aA	188.0 ± 22.8 cB
WY	402.0 ± 57.7 bA	216.6 ± 4.9 cB

151 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 152 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 153 specific weeks, capital letters within specific ochre treatments.

154

155 Ammonium oxalate extractions were used as a proxy for amorphous and poorly crystalline
 156 iron oxides. For the DGC soils the amount of amorphous and poorly crystalline iron oxide

157 was generally greatest for the OM-amended soil and increased over time (Tables 5a,
 158 S9a). The other ochre amendments didn't significantly increase the amount of extractable
 159 iron. A similar trend of increasingly extractable iron over time occurred for the RRT2 soil
 160 (Table 5b, S9b). The amount of extractable iron was lower for the RRT2 than the DGC soil,
 161 despite the same level of Fe amendments. However for the RRT2 soil the ochre
 162 amendments did increase the amount of extractable Fe. The DGC control soil contains more
 163 ammonium extractable Fe than RRT2 (Table 5) suggesting that background iron levels in the
 164 soils might be dominating the results of this extraction for DGC but that for RRT2, iron levels
 165 are sufficiently low for ochre amendments to have a significant impact.

166

167 Table 5a. Acid ammonium extractable Fe in a) DGC and b) RRT2 soil (mg kg⁻¹).

Ochre	Week 3A	Week 12B	Week 24 C	Week 52 D
None a	4.96 ± 1.21	4.92 ± 1.0	7.73 ± 0.73	6.77 ± 0.12
BH a	5.75 ± 0.05	4.46 ± 0.10	7.32 ± 0.09	6.01 ± 0.36
OM b	5.61 ± 0.55	5.11 ± 0.19	9.61 ± 0.07	8.10 ± 0.28
SB a	4.98 ± 0.08	4.30 ± 0.18	8.16 ± 1.1	5.75 ± 0.37
WY a	5.18 ± 1.13	4.31 ± 0.16	8.23 ± 2.6	5.79 ± 0.19

168 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 169 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons between
 170 treatments taking account of all weeks, capital letters between weeks taking account of all
 171 treatments.

172

173 Table 5b.

Ochre	Week 3	Week 12	Week 24	Week 52
None	0.35 ± 0.039 aA	0.33 ± 0.032 aA	0.83 ± 0.57 aB	0.51 ± 0.48 aA
BH	0.74 ± 0.16 bA	0.85 ± 0.048 bA	1.8 ± 0.038 bB	1.7 ± 0.074 bB
OM	1.8 ± 0.16 cA	1.8 ± 0.033 cA	3.9 ± 0.052 cB	4.1 ± 0.080 cB
SB	0.58 ± 0.091 abA	0.46 ± 0.031 aA	1.0 ± 0.0068 aB	0.97 ± 0.0051 dB
WY	0.76 ± 0.069 bA	0.87 ± 0.048 bA	1.4 ± 0.015 dB	1.5 ± 0.039 b B

174 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 175 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 176 specific weeks, capital letters within specific ochre treatments.

177

178 Ochre amendments increased the citrate dithionite extractable iron, a proxy for crystalline
 179 Fe, in both soils, though this increase became less over time (Tables 6, S10) suggesting a

180 gradual loss of crystalline material, possibly as goethite in the ochre degraded, producing
 181 more amorphous material. Assuming that the ochres were pure goethite, the level of ochre
 182 amendment would have resulted in goethite concentrations in the mixtures at or below the
 183 limit of detection of XRD (c. 5%), thus no attempt was made to track changes in Fe
 184 mineralogy in the mixtures using XRD. However, the operationally defined decrease in
 185 crystalline and increase in amorphous Fe oxides is consistent with the Eh-pH data. Goethite
 186 dominated the ochre mineralogy as determined by XRD during material characterisation and
 187 Eh-pH measurements suggest the potential for this phase to be unstable in the ochre
 188 amended soils. Fe oxides are dynamic species that change in soils over time (e.g. Bigham et
 189 al, 2002; Schwertmann and Cornell, 1991). Our incubation study was a year long but it is
 190 possible, given the slow kinetics of many redox reactions, that the mineralogy of the mixtures
 191 was not in steady state but was still changing. This highlights an important consideration for
 192 studies on soil amendments. In addition to laboratory testing, modelling should be carried
 193 out to try and predict the long term stability of the amendments and their impact on
 194 contaminant mobility.

195

196 Table 6a. Citrate dithionite extractable Fe in a) DGC and b) RRT2 soil (mg kg⁻¹).

Ochre	Week 3	Week 12	Week 24	Week 52
None	5.95 ± 0.28 aA	6.92 ± 0.22 aB	5.89 ± 0.61 abA	5.54 ± 0.23 aA
BH	7.34 ± 0.20 bcA	11.3 ± 0.26 bB	6.06 ± 0.50 aC	6.16 ± 0.09 aC
OM	7.21 ± 0.26 bcA	10.5 ± 0.38 cB	5.62 ± 0.16 abC	6.31 ± 0.11 aC
SB	6.66 ± 0.17 abA	9.12 ± 0.56 dB	4.98 ± 0.13 bC	5.74 ± 0.23 aD
WY	8.03 ± 0.15 cA	10.6 ± 0.77 cB	5.33 ± 0.36 abC	6.29 ± 1.7 aD

197 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 198 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 199 specific weeks, capital letters within specific ochre treatments.

200

201

202 Table 6b.

Ochre	Week 3A	Week 12 B	Week 24A	Week 52 C
None a	3.68 ± 0.90	3.45 ± 0.10	2.84 ± 0.09	2.63 ± 0.08
BH b	6.89 ± 0.09	7.97 ± 0.27	7.12 ± 0.24	5.53 ± 0.14
OM c	6.17 ± 1.8	6.93 ± 0.64	6.27 ± 0.49	5.26 ± 0.19
SB d	5.01 ± 0.24	5.97 ± 0.50	5.18 ± 0.47	4.42 ± 0.20
WY b	7.71 ± 0.33	8.53 ± 1.68	7.28 ± 0.56	5.84 ± 0.13

203 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
204 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons between
205 treatments taking account of all weeks, capital letters between weeks taking account of all
206 treatments.

207

208 Typically the adsorption capacity of less well crystalline material is greater than that of more
209 crystalline material (e.g. Jambor and Dutrizac, 1998; Cornell and Schwermann, 2003;
210 Guzman et al., 1994). Thus the conversion of free oxides to amorphous material should lead
211 to an increase in As sorption. This is consistent with the increased efficacy of the ochre
212 treatments (Table 2b). However 0.01 M CaCl₂ extractable As increased with time. This may
213 be due to reductive dissolution of the ochres to Fe²⁺, with amorphous material being an
214 intermediate reaction product. Alternatively or additionally an increase in dissolved organic
215 carbon due to break down of organic matter leading to increased competition for sorption
216 sites between As species and either, or both, dissolved organic matter (DOM) (e.g. Garcia-
217 Sánchez et al., 2010; Gustafsson, 2006; Weng et al, 2009) and phosphate (e.g. Mamindy-
218 Pajany et al., 2011; Sharma and Kappler, 2011; Smith et al., 2002) would lead to an
219 increase in As release. Similar to the possible reductive dissolution of goethite in the ochre,
220 the change in Eh-pH conditions for the RRT2-OM, SB and WY mixtures might cause a
221 change in As speciation from As^V to As^{III}. At the pH of the mixtures, adsorption of As^V is
222 more favourable than that of As^{III} (e.g. Dixit and Hering, 2003; Miretsky and Cirelli, 2010).
223 Thus reduction of As^V could lead to an increase in 0.01 M CaCl₂ extractable As. Such
224 changes could be driven by microbial activity (Páez-Espino et al. 2009; Yamamura and
225 Amachi, 2014). At present we are unable to differentiate between these possible
226 mechanisms. Dissolved organic carbon and phosphate were not measured in our
227 extractions. Although we measured Eh and pH in our mixtures, conditions plot too close to

228 stability field boundaries to be certain of the oxidation state or stability of the phases present.
 229 A more detailed spectroscopic investigation to determine Fe and As speciation would be
 230 required to resolve this. This highlights the importance of Eh-pH conditions when considering
 231 Fe amendments and As remediation. Additionally the possible increase in sorption capacity
 232 of the ochre (Table 2) due to conversion of crystalline to amorphous Fe oxyhydroxides
 233 coupled with potential desorption of As from ochres due to interaction with DOM, phosphate
 234 and changing As speciation highlights the difficulties in extrapolating from simple laboratory-
 235 based adsorption experiments to interactions in the field.

236

237 Microbial activity, determined using a FDA hydrolysis assay, which estimates the total
 238 hydrolytic capacity of soils, was greatest after 3 weeks of incubation ($p \leq 0.01$) for both soils
 239 (Table 7). Prior to incubation the soil had been air-dried and sieved. Initial peaks in microbial
 240 activity are commonly observed when dry, sieved soil is moistened since microbial
 241 metabolism is no longer constrained by desiccation and there is enhanced substrate
 242 availability due to: (i) production of cytoplasmic solutes by the microbial biomass in response
 243 to the rapid increase in soil water potentials (Fierer and Schimel, 2003) and (ii) exposure of
 244 previously physically protected organic matter as a result of sieving (Franzluebbers, 1999)
 245 and rewetting (Fierer and Schimel, 2003). Initially, activity was greater in the WY amended
 246 soils but from Week 12 onwards there were no significant differences between control and
 247 ochre-amended soils (Table 7, S11).

248

249 Table 7a. Microbial activity (μg fluorescein per gram dry soil per 0.5 h) in a) DGC and b)
 250 RRT2 soil.

Ochre	Week 3	Week 12	Week 24	Week 52
None	29.6 \pm 9.21 aA	16.1 \pm 3.89 aB	5.05 \pm 1.06 aC	7.51 \pm 1.96 aC
BH	30.2 \pm 6.23 aA	10.9 \pm 1.37 aB	9.02 \pm 0.950 aB	7.00 \pm 1.46 aB
OM	41.2 \pm 9.79 bA	12.8 \pm 0.782 aB	15.3 \pm 7.29 aB	15.0 \pm 2.60 aB
SB	29.0 \pm 8.45 aA	10.1 \pm 1.97 aB	6.54 \pm 1.83 aB	10.3 \pm 0.798 aB
WY	48.8 \pm 17.0 bA	15.3 \pm 2.65 aB	14.3 \pm 2.64 aB	16.2 \pm 3.57 aB

251 Values are means of 5 replicates \pm standard deviation. Same letters = not significantly
252 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
253 specific weeks, capital letters within specific ochre treatments.

254

255

256 Table 7b.

Ochre	Week 3	Week 12	Week 24	Week 52
None	38.4 ± 9.44aA	19.2 ± 3.00aB	24.9 ± 3.40aB	22.7 ± 2.47aB
BH	37.6 ± 6.16aA	18.1 ± 5.18aB	20.8 ± 5.56aB	21.0 ± 2.19aB
OM	41.0 ± 6.17aA	16.9 ± 3.38aB	27.5 ± 2.86aC	24.3 ± 2.61aC
SB	35.9 ± 8.11aA	19.7 ± 7.41aB	21.5 ± 2.84aB	20.8 ± 4.74aB
WY	51.6 ± 9.27bA	15.7 ± 2.05aB	22.2 ± 3.13aB	18.8 ± 3.51aB

257 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 258 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 259 specific weeks, capital letters within specific ochre treatments.

260

261 Our initial extractions suggest that ochre amendments can reduce the amount of 0.01 M
 262 CaCl_2 extractable As from As-contaminated soils, most likely due to sorption of As to iron
 263 oxyhydroxides. However, ochre amendment, with the exception for OM (DGC soil) and WY
 264 (DGC and RRT2 soil) ochre at week 3 (Table 7a), does not cause a significant increase in
 265 microbial activity. In week 3, the increased microbial activity in the OM and WY ochre
 266 amended DGC soils corresponded to the most pronounced ochre-induced reductions in As
 267 mobility. Arsenic can cause microbial toxicity (Páez-Espino et al. 2009; Yamamura and
 268 Amachi, 2014) so this result could be interpreted as ochre-mediated alleviation of As toxicity.
 269 However, in subsequent weeks As mobility increases whilst microbial activity remains
 270 constant and As mobility is greater in the non-amended soils whilst there is no difference in
 271 microbial activity between amended and non-amended soils (Tables 2a, 7). The differential
 272 response in week 3 might be related to the rehydration of the soil at the start of the
 273 experiment. As previously explained, this would likely have resulted in a flush of available
 274 substrate and it is possible that microorganisms in OM and WY ochre amended DGC soils
 275 were more able to respond to this flush as a result of reduced As toxicity (or elevated pH) in
 276 these treatments; once rehydration effects subsided effects of ochre amendment on
 277 microbial activity were no longer detectable.

278

279 At 3, 12, 24 and 52 weeks subsamples of soil were taken and used in plant bioassays. Rye
 280 grass was grown in the soil for 40 days, harvested and then biomass and plant As content

281 assessed. For both soils generally there was no difference in root biomass with treatment
 282 (Table S12, S13) whereas shoot biomass generally increased in the WY and, for RRT2, OM
 283 amended soils (Tables 8, S14). Arsenic concentrations in shoots and roots showed a large
 284 amount of variation within replicates, potentially indicating adhesion of soil particles to the
 285 plant material used in the digestions (e.g. Markert, 1995) as has been found to be
 286 problematic in previous studies (e.g. Doi et al., 2005; Walsh and Keeny, 1975). Arsenic
 287 concentrations were greater in roots than shoots (Tables 9, 10). For the DGC soil, WY
 288 amendments initially reduced As uptake into shoots but over time uptake of As from
 289 untreated DGC soil decreased and by week 24 there was no significant effect of the ochre
 290 amendments (Tables 9a, S15a). For the RRT2 soil there is a similar decrease in As uptake
 291 into shoots over time but no significant impact of ochre on As uptake (Tables 9b, S15b). For
 292 roots, there is a similar decrease in As uptake with duration of incubation for the DGC soil so
 293 that initially significant reductions in As uptake due to addition of ochre ($p \leq 0.01$) are not
 294 significant after 52 weeks incubation (Tables 10a, S16a). For the RRT2 roots uptake was
 295 significantly higher in week 3 compared to weeks 12, 24 and 52 ($p \leq 0.01$) but there was no
 296 significant effect of the ochre amendments (Table 10b, S16b).

297

298 Table 8a. Shoot biomass (mg) for *Lolium perenne* grown in a) DGC and b) RRT2 soil.

Ochre	Week 3	Week 12	Week 24	Week 52
None	20.4 ± 9.90 aA	62.0 ± 17.6 aB	68.0 ± 17.2 aB	15.0 ± 3.20 aA
BH	48.2 ± 20.8 abA	46.2 ± 14.5 aA	57.0 ± 29.0 aA	12.4 ± 5.60 aB
OM	65.0 ± 10.8 bcA	58.6 ± 22.5 aA	70.2 ± 4.30 aA	18.0 ± 8.50 aB
SB	86.2 ± 7.50 cA	73.4 ± 30.1 aA	70.0 ± 40.7 aA	8.20 ± 4.40 aB
WY	132 ± 10.4 dA	211 ± 43.7 bB	133 ± 15.0 bA	33.2 ± 8.60 aC

299 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 300 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 301 specific weeks, capital letters within specific ochre treatments.

302

303

304 Table 8b.

Ochre	Week 3	Week 12	Week 24	Week 52
None	37.2 ± 27.7 aA	178 ± 18.5 aB	109 ± 30.0 aAB	71.8 ± 10.0 aA
BH	65.2 ± 30.8 abAB	182 ± 68.4 aC	144 ± 53.5 aAC	84.8 ± 14.2 aB
OM	109 ± 68.7 abA	313 ± 55.5 bB	307 ± 81.9 bB	267 ± 32.5 bB
SB	52.6 ± 39.4 aA	58.8 ± 21.2 cA	76.2 ± 17.7 aA	26.8 ± 5.60 aA
WY	142.2 ± 20.0 bA	284 ± 24.4 bB	289 ± 85.1 bB	246 ± 43.6 bB

305 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 306 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 307 specific weeks, capital letters within specific ochre treatments.

308

309 Table 9a. Shoot As (mg kg^{-1}) for *Lolium perenne* grown in a) DGC and b) RRT2 soil.

Ochre	Week 3	Week 12	Week 24	Week 52
None	983 ± 594 aA	2005 ± 1081 aB	297 ± 95.4 aC	221 ± 153 aC
BH	368 ± 169 abAB	795 ± 309 bA	356 ± 131 aAB	46.4 ± 37.0 aB
OM	890 ± 723 aA	122 ± 43.2 cB	169 ± 95.7 aB	72.0 ± 76.0 aB
SB	745 ± 446 abA	523 ± 186 bcA	290 ± 184 aA	427 ± 338 aA
WY	171 ± 131 bA	350 ± 162 bcA	259 ± 114 aA	325 ± 334 aA

310 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 311 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 312 specific weeks, capital letters within specific ochre treatments.

313

314 Table 9b.

Ochre	Week 3 A	Week 12B	Week 24B	Week 52B
None a	255 ± 375	145 ± 192	19.1 ± 4.72	50.7 ± 40.4
BH a	144 ± 86.9	31.2 ± 27.1	13.2 ± 5.75	43.3 ± 55.3
OM a	105 ± 85.6	9.17 ± 6.00	9.69 ± 2.52	14.6 ± 8.17
SB a	89.9 ± 32.1	61.0 ± 56.7	16.6 ± 5.78	39.2 ± 19.3
WY a	23.9 ± 22.4	10.5 ± 3.96	9.63 ± 4.24	11.7 ± 7.88

315 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 316 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons between
 317 treatments taking account of all weeks, capital letters between weeks taking account of all
 318 treatments.

319

320

321 Table 10a. Root As (mg kg⁻¹) for *Lolium perenne* grown in a) DGC and b) RRT2 soil.

Ochre	Week 3	Week 12	Week 24	Week 52
None	5350± 2110 abcA	2460± 779 aB	1830± 346 aB	1350± 418 aB
BH	3130± 1400 dA	2100± 273 bA	1450± 817 aA	1560± 969 aA
OM	7470± 3260 bA	1640± 388 cB	1020± 235 aB	773± 457 aB
SB	3330± 2380 cdA	2180± 974 bcA	1340± 560 aA	1270± 614 aA
WY	4710± 1310 cdA	3630± 1478 bcA	963± 366 aB	641± 279 aB

322 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 323 different ($p \leq 0.05$, Holm-Sidak method). Lower case letters are for comparisons within
 324 specific weeks, capital letters within specific ochre treatments.

325

326 Table 10b.

Ochre	Week 3 A	Week 12B	Week 24B	Week 52B
None a	445± 214	171 ± 48.6	103 ± 36.2	96.3 ± 65.7
BH a	789 ± 883	138 ± 22.4	63.9 ± 44.2	48.9 ± 21.2
OM a	604 ± 286	121 ± 23.8	60.9 ± 11.5	56.1 ± 30.7
SB a	266 ± 65.0	107 ± 32.0	95.7 ± 25.8	148 ± 174
WY a	431 ± 199	83.7 ± 15.5	88.0 ± 9.84	71.6 ± 15.9

327 Values are means of 5 replicates ± standard deviation. Same letters = not significantly
 328 different ($p \leq 0.05$; Holm-Sidak method). Lower case letters are for comparisons between
 329 treatments taking account of all weeks, capital letters between weeks taking account of all
 330 treatments.

331

332 Ochre amendments had little benefit in terms of plant growth promotion and As uptake
 333 reduction. Higher levels of As in the DGC soil and lower pH clearly had a significant impact
 334 on plant growth compared to the RRT2 soil. Root biomass was similar between the two soils
 335 despite the higher As content of the DGC roots whereas shoot biomass was lower and shoot
 336 As concentration was higher in the DGC soil. This further suggests that some of the “root As”
 337 in the DGC roots was actually due to adhering soil particles or that root growth is less
 338 sensitive to As than shoot growth. Given the reduction in CaCl₂ extractable As due to ochre
 339 addition and the increase in CaCl₂ extractable As over time the lack of a significant impact of
 340 ochre on plant uptake and decrease in plant uptake from the soils that had been incubated
 341 for longer was surprising. This suggests that As uptake may be dominated by rhizosphere
 342 processes at a scale that the extraction of As from bulk soil is unable to resolve.

343

344 Due to time constraints the PBET was only applied to soils incubated for 3 and 52 weeks.
345 For the DGC and RRT2 stomach phase and the DGC intestine phase, significantly more As
346 was extracted after 52 weeks incubation compared to 3 weeks incubation for both soils and
347 all treatments ($p \leq 0.01$) (Tables 11, S17), consistent with the increase in CaCl_2 extractable
348 As (Table 2). For the RRT2 soil, ochre amendments reduced extractable As ($p \leq 0.01$) but this
349 wasn't the case for the DGC soil; this may be due to the pH differences of the soils. RRT2
350 had a higher pH than DGC and the soil-ochre mixtures may have buffered the low pH of the
351 PBET extraction to a greater extent, resulting in less As release. Extractable As in the
352 intestine phase for the RRT2 soil was below detection ($121.95 \text{ mg kg}^{-1}$).

353

354 **Conclusions**

355 The adsorption and batch experiments suggest that waste ochre may have a role to play in
356 treating As-contaminated water. However further research would be required to establish the
357 Eh-pH stability field of the ochres, the impact of time on ochre composition and sorption
358 capacity, the impact of water chemistry e.g. ionic strength, dissolved organic carbon on
359 sorption, and a means of deploying the ochre in water courses, possibly via incorporation
360 into a semi-permeable membrane.

361

362 On the basis of the soil incubation study it is not possible to recommend ochre amendments
363 to As-contaminated soils as a remedial treatment. Although the amendments may reduce
364 transfer of As to water courses they do not impact reliably on other significant pathways of
365 As transfer through the environment, i.e. uptake by plants and release of As following
366 ingestion of As-contaminated soil by humans. Additionally it is not clear that the ochres are
367 stable in the amended soils and therefore the long term impacts on extractable As are not

368 clear. A more detailed investigation into soil Eh and both ochre and As speciation would be
369 required coupled with modelling studies to cast further light on this.

370

371 The well documented sorption of a variety of elements to Fe oxides does suggest that the
372 use of ochres for the remediation of multi-element contaminated waters and soils may be
373 worth investigating for situations with appropriate Eh-pH conditions.

374

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382 helped improve this manuscript.

383

Table 11. As concentration (mg kg⁻¹) in the stomach phase of the PBET extraction.

Soil Ochre	DGC - stomach		DGC – intestine		RRT2 - stomach	
	Week 3 A	Week 52 B	Week 3 A	Week 52 B	Week 3A	Week 52B
None	93.7 ± 2.73a	122 ± 32.9	517 ± 168 a	707 ± 96.0	8.24 ± 0.326a	25.0 ± 3.62
BH	120 ± 2.45a	164 ± 49.3	623 ± 112 a	685 ± 53.2	3.53 ± 1.76b	14.1 ± 1.66
OM	112 ± 1.82ab	185 ± 25.4	474 ± 10.3 a	796 ± 190	3.54 ± 1.23b	16.5 ± 4.06
SB	97.7 ± 7.97a	146 ± 27.9	423 ± 51.3 a	582 ± 187	1.95 ± 1.30b	18.0 ± 1.14
WY	133 ± 5.97b	264 ± 49.6	585 ± 106 a	879 ± 102	2.61 ± 0.953b	16.1 ± 0.290

Values are means of 3 replicates ± standard deviation. For each set of data (DGC- stomach, DGC – intestine, RRT2 – stomach) same letters = not significantly different ($p \leq 0.05$; Holm-Sidak method); lower case letters are for comparisons between treatments taking account of both weeks 3 and 52 (letters shown in week 3 column for clarity), capital letters between weeks 3 and 52 taking account of all treatments.

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220

221 **Supplementary material**

222

223 **Does ochre have the potential to be a remedial treatment for As-contaminated soils?**

224

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234

235 **Characterisation of soils and ochres**

236 pH was measured on a suspension of 10 g material in 25 mL deionised water that was
237 shaken for 15 minutes at 20 ± 1 °C on an end-over-end shaker prior to measurement with a
238 Jenway 3310 pH meter calibrated using pH 7.00 and 4.00 buffers (ISO, 2005). Loss on
239 ignition was determined as a proxy for organic matter content by oven drying the soils and
240 ochres at 105 °C overnight and then igniting overnight at 500 °C in a muffle furnace (Rowell,
241 1994). It should be noted that calcium carbonate and clays can degrade at this temperature
242 potentially giving misleadingly high values for the ochre samples. Particle size distribution
243 was determined using a Beckman Coulter LS230 laser granulometer with a variable fluid
244 module and Polarisation intensity differential scattering (PIDS) system. Particle size

245 calculations were made using the Fraunhofer optical model system (de Boer et al., 1987).
246 BET surface area was determined by gas adsorption and application of the BET isotherm
247 (Brunauer et al., 1938) using a Gemini III 2375 surface area analyser; samples were
248 degassed overnight at 60 °C with a N₂ purge. Total As and Fe of the samples was
249 determined by aqua regia digestion (Arnold et al., 2008) followed by analysis using a Perkin
250 Elmer Optima 3000 inductively coupled plasma-optical emission spectrometer (ICP-OES).
251 The iron content of the ochre was further characterised by acid ammonium oxalate and
252 citrate-bicarbonate-dithionite extractions (Loeppert and Inskeep, 1996) to determine
253 amorphous / poorly crystalline forms of Fe oxides and free Fe oxides respectively. Resulting
254 solutions were analysed by ICP-OES. The point of zero charge of the ochres was
255 determined after the method of Zelazny et al. (1996) which was adapted from Uehara and
256 Gillman (1982). In brief, the ochres were allowed to adsorb K⁺ and Cl⁻ in an electrolyte of 1 M
257 KCl over a range of pH values; the amount of adsorbed K⁺ and Cl⁻ were taken as the
258 quantities of negative and positive surface charge at each pH and the PZNC taken as the pH
259 at which these two values were equal and opposite. Mineralogy was determined on
260 randomly oriented samples of ground material using a Siemens D5000 X-ray diffractometer
261 using Cu K α radiation at 40 keV and 40 mA, with a scanning range of 4° – 64°, 20 steps per
262 degree and a dwell time of 2 seconds.

263

264 **Analytical details for measurements made on the incubation experiment soils**

265 ***Eh measurement***

266 The redox potential of the incubated soil samples was monitored using a platinum electrode,
267 redox solution and a millivolt meter. An initial test was conducted by inserting the platinum
268 electrode into the standard redox solution to ascertain that the meter and the electrode were
269 working within the normal range (200 to 275 mV) (Hanna Instrument). Inserting the electrode
270 into redox standard solution for about 1 hour before measurement helps to ensure stable
271 reading and prevents fluctuation. To take the redox measurement, the platinum electrode

272 was inserted into the wet soil and allowed to stabilize for one minute before recording the
273 reading from a millivolt meter (Hanna pH 21 pH/mV). The electrode was rinsed with
274 deionised water and then wiped with soft tissue between measurements.

275

276 ***Plant bioassays***

277 For the plant bioassays, plant pots lined with filter paper to aid soil retention were filled with
278 150 g of the wet incubated soil. Rye grass seeds (0.5 g per pot, purchased from Herbiseed,
279 New Farm, Mire Lane, West End, Twyford, England) were added to the surface of the soil.
280 Plant pots were set out in a completely randomized design in a plant growth room subject to
281 un-monitored ambient temperature and a lighting regime of 150 – 300 micromoles $\text{m}^{-2} \text{s}^{-1}$
282 with a photoperiod of 17 hours. The average amount of water lost from each pot over two
283 days due to evaporation and transpiration was assessed by mass loss as 15 mL. This
284 volume of deionised water was added to the pots every other day. After 40 days plants were
285 harvested. Shoots were cut 1 cm above ground level. Roots were washed in deionised water
286 to remove attached soil. Plant samples were dried at 70 °C to a constant mass which was
287 recorded and then ground using an agate pestle and mortar prior to acid digestion using an
288 in house nitric acid digestion method. This method involved addition of 5 mL of 1M HNO_3 to
289 ≤ 0.25 g of plant material in digestion tubes. Following HNO_3 addition, samples were left
290 overnight and subsequently heated to 60 °C and left for 3 hours. The temperature was
291 raised to 110 °C and the samples digested for a further 6 hours. After cooling samples were
292 filtered, diluted as necessary and analysed for As by ICP-OES.

293

294 ***PBET extraction***

295 The PBET extraction followed that of Intawongse and Dean, (2008). In brief 1 g of air dried,
296 $\leq 250 \mu\text{m}$ soil was shaken with 100 mL simulated gastric acid solution at 150 oscillations per
297 hour for one hour at 37 °C. 5 mL of solution was filtered through a 0.45 μm cellulose filter

298 and analysed for As by ICP-OES. This was the stomach phase. The gastric acid solution
299 comprised 2.5 g pepsin, 1 g sodium malate, 1 g sodium citrate, 1 mL acetic acid and 0.84
300 mL lactic acid made up to 2 L with ultra pure water and with the pH adjusted to 2.5 using
301 concentrated hydrochloric acid (stomach phase). Saturated sodium bicarbonate solution was
302 added dropwise to the remaining solution until a pH of 7 was reached. Bile salt (0.175 g) and
303 pancreatin (0.05 g) were added and the solution shaken at 37 °C for a further 4 hours after
304 which time 5 mL of solution was filtered and analysed for As by ICP-OES. This was the small
305 intestine phase. In initial tests a sample was taken at 2 and 4 hours but comparison of the 2
306 and 4 hour samples indicated that equilibrium had not been reached after 2 hours.

307

308 ***Fluorescein diacetate (FDA) hydrolysis assay***

309 The FDA hydrolysis assay followed the method of (Adam and Duncan, 2001). Soil samples
310 (1 g wet weight) in sterile McCartney bottles were amended with 7.5 ml of warmed (26 °C)
311 sterile potassium phosphate buffer (60 mM, pH 7.6) and allowed to equilibrate at 26 °C on a
312 reciprocating shaker for 2 minutes. The assay was initiated by addition of 0.1 ml FDA
313 (Sigma-Aldrich) substrate solution (1000 µg/ml in acetone) to each tube and tubes were
314 incubated (26 °C) with shaking for 30 minutes after which time the assay was stopped by
315 addition of 7.5 ml of chloroform:methanol (2:1). Tubes were vortex mixed (10 s) and then
316 centrifuged at low speed (~300 g, 2 mins) to clarify the phases. The upper phase (2 ml) was
317 further centrifuged (13,000 x g, 5 mins) to remove suspended fines prior to determination of
318 absorbance at 490 nm (Cecil CE292 Spectrophotometer). Absorbance readings were
319 compared to a calibration curve for fluorescein disodium salt (0-5 µg ml⁻¹ in potassium
320 phosphate buffer, 60 mM, pH 7.6). To correct for extraction of soil compounds absorbing at
321 490 nm, blank samples amended with 0.1 ml of acetone instead of FDA solution were
322 included. To check for abiotic hydrolysis of FDA, the above assay was also conducted for
323 autoclaved soil samples (15 minutes at 15 psi) but negligible abiotic hydrolysis was
324 recorded.

326 Supporting Table S1. 3 way ANOVA table for 200 mg L⁻¹ adsorption experiment.

Source of variation	df	SS	MS	F	P-value
Ochre	3	7.24 x 10 ¹⁰	2.41 x 10 ¹⁰	7152.985	< 0.001
Time	4	4.33 x 10 ⁸	1.08 x 10 ⁸	32.102	< 0.001
pH	1	2.03 x 10 ⁹	2.03 x 10 ⁹	602.118	< 0.001
Ochre x time	12	2.11 x 10 ⁸	1.76 x 10 ⁷	5.214	< 0.001
Ochre x pH	3	2.64 x 10 ⁸	8.81 x 10 ⁷	26.107	< 0.001
Time x pH	4	8.95 x 10 ⁷	2.24 x 10 ⁷	6.630	< 0.001
Ochre x time x pH	12	1.06 x 10 ⁸	8.82 x 10 ⁶	2.614	0.005
Residual	80	2.70 x 10 ⁸	3.37 x 10 ⁶		
Total	119	7.58 x 10 ¹⁰	6.37 x 10 ⁸		

327

328

329 Supporting Table S2. 3 way ANOVA table for 500 mg L⁻¹ adsorption experiment.

Source of variation	df	SS	MS	<i>F</i>	<i>P</i> -value
Ochre	3	1.37 x 10 ¹⁰	4.56 x 10 ⁹	347.362	< 0.001
Time	4	2.04 x 10 ⁹	5.10 x 10 ⁸	38.867	< 0.001
pH	1	5.63 x 10 ⁹	5.63 x 10 ⁹	428.674	< 0.001
Ochre x time	12	3.75 x 10 ⁹	3.13 x 10 ⁸	23.838	< 0.001
Ochre x pH	3	2.55 x 10 ⁹	8.52 x 10 ⁸	64.893	< 0.001
Time x pH	4	6.47 x 10 ⁸	1.62 x 10 ⁸	12.331	< 0.001
Ochre x time x pH	12	3.11 x 10 ⁹	2.59 x 10 ⁸	19.753	< 0.001
Residual	80	1.05 x 10 ⁹	1.31 x 10 ⁷		
Total	119	3.25 x 10 ¹⁰	2.73 x 10 ⁸		

330

331

332 Supporting Table S3. 3 way ANOVA for 24 hour data from the As – ochre adsorption
 333 experiment.

Source of variation	df	SS	MS	F	P-value
As concentration	1	1.35×10^8	1.35×10^8	13.443	< 0.001
Ochre	3	1.54×10^{10}	5.12×10^9	510.746	< 0.001
pH	1	2.37×10^9	2.37×10^9	235.838	< 0.001
As concentration x ochre	3	2.57×10^9	8.55×10^8	85.27	< 0.001
As concentration x pH	1	1.75×10^8	1.75×10^8	17.483	< 0.001
Ochre x pH	3	2.73×10^8	9.11×10^7	9.078	< 0.001
As concentration x ochre x pH	3	2.59×10^8	8.63×10^7	8.606	< 0.001
Residual	32	3.21×10^8	1.00×10^7		
Total	47	2.15×10^{10}	4.57×10^8		

334

335

336 Supporting Table S4. 2 way ANOVA for batch experiment study using DGC soil.

Source of variation	df	SS	MS	<i>F</i>	<i>P</i> -value
Ochre type	3	1063.729	354.576	33.740	< 0.001
Ochre mass	4	21993.122	5498.280	523.190	< 0.001
Ochre type x ochre mass	12	1653.643	137.804	13.113	< 0.001
Residual	40	420.366	10.509		
Total	59	25130.860	425.947		

337

338 Supporting Table S5. pH of DGC batch experiment suspensions. Mean \pm standard deviation,
339 n = 3.

Ochre	Mass / g	pH	
-	-	2.46	0.04
BH	0.05	3.02	0.08
BH	0.1	3.44	0.11
BH	0.2	3.65	0.23
BH	0.5	4.16	0.09
OM	0.05	4.16	0.09
OM	0.1	4.08	0.08
OM	0.2	5.13	0.09
OM	0.5	5.91	0.03
SB	0.05	3.27	0.08
SB	0.1	3.56	0.02
SB	0.2	3.98	0.07
SB	0.5	4.63	0.13
WY	0.05	4.28	0.26
WY	0.1	4.48	0.07
WY	0.2	5.25	0.09
WY	0.5	5.92	0.14

340

341

342 Supporting Table S6. Two way repeated measures ANOVA for 0.01M CaCl₂ extractable As
343 from DGC soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	114.752	28.688	843.962	<0.001
Rep(Ochre)	20	0.680	0.0340		
Week	3	110.236	36.745	788.742	<0.001
Ochre x Week	12	38.614	3.218	69.070	<0.001
Residual	60	2.795	0.0466		
Total			99	267.077	2.698

344

345

346 Supporting Table S7a. Two way repeated measures ANOVA for pH of DGC soil with ochre
 347 and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	6.391	1.598	574.789	<0.001
Subject(Ochre)	20	0.0556	0.00278		
Week	3	0.743	0.248	162.694	<0.001
Ochre x Week	12	0.553	0.0461	30.293	<0.001
Residual	60	0.0913	0.00152		
Total	99	7.833	0.0791		

348

349 Supporting Table S7b. Two way repeated measures ANOVA for pH of RRT2 soil with ochre
 350 and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	8.457	2.114	311.268	<0.001
Subject(Ochre)	20	0.136	0.00679		
Week	3	1.085	0.362	77.878	<0.001
Ochre x Week	12	0.473	0.0394	8.488	<0.001
Residual	60	0.279	0.00464		
Total	99	10.428	0.105		

351

352

353 Supporting Table S8a. Two way repeated measures ANOVA for Eh of DGC soil with ochre
 354 and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	12309	3077	3.542	0.03
Subject(Ochre)	4	3685	921		
Week	1	25946	25946	24.126	< 0.01
Ochre x Week	4	15194	3798	3.663	0.027
Residual	16	16590	1036.895		
Total	49	91924.5	1876.01		

355

356 Supporting Table S8b. Two way repeated measures ANOVA for Eh of RRT2 soil with ochre
 357 and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	235357	58839	54.105	< 0.001
Subject(Ochre)	4	13752	3438		
Week	1	342626	342626	148.145	< 0.001
Ochre x Week	4	134818	33704	34.877	< 0.001
Residual	16	15462	966		
Total	49	768667	15687		

358

359

360 Supporting Table S9a. Two way repeated measures ANOVA for acid ammonium oxalate
 361 extractable Fe in DGC soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	23.732	5.933	12.734	<0.001
Subject(Ochre)	20	9.318	0.466		
Week	3	185.719	61.906	86.968	<0.001
Ochre x Week	12	16.240	1.353	1.901	0.052
Residual	60	42.710	0.712		
Total	99	277.718	2.805		

362

363 Supporting Table S9b. Two way repeated measures ANOVA for acid ammonium oxalate
 364 extractable Fe in RRT2 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	69.066	17.266	580.176	<0.001
Subject(Ochre)	20	0.595	0.0298		
Week	3	20.989	6.996	212.395	<0.001
Ochre x Week	12	11.666	0.972	29.513	<0.001
Residual	60	1.976	0.0329		
Total	99	104.292	1.053		

365

366

367 Supporting Table S10a. Two way repeated measures ANOVA for citrate dithionite
 368 extractable Fe in DGC soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	39.359	9.840	52.429	<0.001
Subject(Ochre)	20	3.754	0.188		
Week	3	255.968	85.323	281.600	<0.001
Ochre x Week	12	39.693	3.308	10.917	<0.001
Residual	60	18.180	0.303		
Total	99	356.953	3.606		

369

370 Supporting Table S10b. Two way repeated measures ANOVA for citrate dithionite
 371 extractable Fe in RRT2 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	221.786	55.447	95.180	<0.001
Subject(Ochre)	20	11.651	0.583		
Week	3	42.857	14.286	37.666	<0.001
Ochre x Week	12	8.250	0.687	1.813	0.066
Residual	60	22.756	0.379		
Total	99	307.300	3.104		

372

373

374 Supporting Table S11a Two way repeated measures ANOVA for microbial activity in DGC
 375 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	1640.811	410.203	10.438	<0.001
Subject(Ochre)	20	785.987	39.299		
Week	3	11224.440	3741.480	111.141	<0.001
Ochre x Week	12	854.317	71.193	2.115	0.029
Residual	60	2019.850	33.664		
Total	99	16525.404	166.923		

376
 377 Supporting Table S11b Two way repeated measures ANOVA for microbial activity in RRT2
 378 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	164.970	41.243	1.269	0.315
Subject(Ochre)	20	649.971	32.499		
Week	3	7859.502	2619.834	102.950	< 0.001
Ochre x Week	12	918.275	76.523	3.007	0.002
Residual	60	1526.864	25.448		
Total	99	11119.583	112.319		

379
 380

381 Supporting Table S12a Root biomass (mg) for *Lolium perenne* in DGC soil. Values are mean
 382 \pm standard deviation, n = 5

Ochre	Week 3	Week 12	Week 24	Week 52
None	236 \pm 43.5 aA	231 \pm 21.3 aA	239 \pm 50.7 aA	211 \pm 44.0 abA
BH	204 \pm 34.2 aA	309 \pm 77.1 aB	206 \pm 30.4 aA	312 \pm 65.5 cB
OM	280 \pm 61.8 aAB	318 \pm 83.4 aA	228 \pm 61.5 aB	238 \pm 74.8 abcAB
SB	196 \pm 42.6 aA	298 \pm 31.0 aB	175 \pm 66.8 aA	288 \pm 55.6 acB
WY	217 \pm 11.6 aA	321 \pm 42.2 aB	223 \pm 13.9 aA	171 \pm 47.7 bA

383 Same letters = not significantly different ($p \leq 0.05$, Holm-Sidak method). Lower case letters
 384 are for comparisons within specific weeks, capital letters within specific ochre treatments.

385

386 Supporting Table S12b Two way repeated measures ANOVA for root biomass in DGC soil
 387 with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	0.0205	0.00513	1.840	0.161
Subject(Ochre)	20	0.0557	0.00279		
Week	3	0.0954	0.0318	11.892	<0.001
Ochre x Week	12	0.107	0.00888	3.320	<0.001
Residual	60	0.160	0.00267		
Total	99	0.439	0.00443		

388

389

390 Supporting Table S13a Root biomass (mg) for *Lolium perenne* in RRT2 soil. Values are
 391 mean \pm standard deviation, n = 5

Ochre	Week 3 AB	Week 12 C	Week 24 A	Week 52 BC
None a	246 \pm 117	301 \pm 60.1	274 \pm 64.1	302 \pm 50.3
BH a	246 \pm 25.2	312 \pm 52.3	224 \pm 25.0	302 \pm 13.7
OM a	298 \pm 70.8	350 \pm 72.5	273 \pm 40.9	351 \pm 58.8
SB a	266 \pm 49.7	364 \pm 47.6	208 \pm 10.7	237 \pm 83.2
WY a	266 \pm 83.0	306 \pm 38.5	296 \pm 10.8	367 \pm 23.6

392 Same letters = not significantly different ($p \leq 0.05$, Holm-Sidak method). Lower case letters
 393 are for comparisons between treatments taking account of all weeks, capital letters between
 394 weeks taking account of all treatments.

395

396 Supplementary Table S13b Two way repeated measures ANOVA for root biomass in RRT2
 397 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	0.0406	0.0101	2.440	0.080
Subject(Ochre)	20	0.0831	0.00416		
Week	3	0.0927	0.0309	5.463	0.002
Ochre x Week	12	0.0646	0.00539	0.952	0.504
Residual	60	0.339	0.00566		
Total	99	0.621	0.00627		

398

399

400 Supplementary Table S14a. Two way repeated measures ANOVA for shoot biomass in DGC
 401 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	0.104	0.0261	68.646	<0.001
Subject(Ochre)	20	0.00760	0.000380		
Week	3	0.0789	0.0263	65.619	<0.001
Ochre x Week	12	0.0452	0.00377	9.401	<0.001
Residual	60	0.0240	0.000401		
Total	99	0.260	0.00263		

402

403 Supplementary Table S14b. Two way repeated measures ANOVA for shoot biomass in
 404 RRT2 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	0.615	0.154	117.064	<0.001
Subject(Ochre)	20	0.0262	0.00131		
Week	3	0.223	0.0742	34.467	<0.001
Ochre x Week	12	0.0888	0.00740	3.437	<0.001
Residual	60	0.129	0.00215		
Total	99	1.081	0.0109		

405

406

407 Supplementary Table S15a. Two way repeated measures ANOVA for shoot As
 408 concentration in DGC soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	4681477.751	1170369.438	9.271	<0.001
Rep(Ochre)	20	2524764.918	126238.246		
Week	3	5282175.276	1760725.092	12.267	<0.001
Ochre x Week	12	9273522.998	772793.583	5.384	<0.001
Residual	60	8612054.281	143534.238		
Total	99	30373995.225	306808.033		

409

410 Supplementary Table S15b. Two way repeated measures ANOVA for shoot As
 411 concentration in RRT2 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	120724.599	30181.150	1.822	0.164
Rep(Ochre)	20	331377.515	16568.876		
Week	3	173700.230	57900.077	7.217	<0.001
Ochre x Week	12	95351.017	7945.918	0.990	0.469
Residual	60	481387.017	8023.117		
Total	99	1202540.378	12146.873		

412

413

414 Supplementary Table S16a. Two way repeated measures ANOVA for root As concentration
 415 in DGC soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	9642079.845	2410519.961	1.807	0.167
Subject(Ochre)	20	26676327.492	1333816.375		
Week	3	212977061.332	70992353.777	42.979	<0.001
Ochre x Week	12	69018419.756	5751534.980	3.482	<0.001
Residual	60	99107737.411	1651795.624		
Total	99	417421625.836	4216380.059		

416

417 Supplementary Table S16b. Two way repeated measures ANOVA for root As concentration
 418 in RRT2 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	135865.248	33966.312	0.739	0.576
Subject(Ochre)	20	918747.592	45937.380		
Week	3	3185131.596	1061710.532	20.756	<0.001
Ochre x Week	12	708377.885	59031.490	1.154	0.336
Residual	60	3069064.889	51151.081		
Total	99	8017187.211	80981.689		

419

420

421 Supplementary Table S17a. Two way repeated measures ANOVA for stomach extractable
 422 As in DGC soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	28738.914	7184.728	9.872	0.002
Col 1(Ochre)	10	7277.793	727.779		
Week	1	31558.150	31558.150	40.713	<0.001
Ochre x Week	4	9592.818	2398.204	3.094	0.067
Residual	10	7751.420	775.142		
Total	29	84919.095	2928.245		

423

424 Supplementary Table 17b. Two way repeated measures ANOVA for stomach extractable As
 425 in RRT2 soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	245.125	61.281	11.616	<0.001
Col 1(Ochre)	10	52.754	5.275		
Week	1	1459.669	1459.669	499.707	<0.001
Ochre x Week	4	36.869	9.217	3.155	0.064
Residual	10	29.211	2.921		
Total	29	1823.627	62.884		

426

427 Supplementary Table 17c. Two way repeated measures ANOVA for intestine extractable As
 428 in DGC soil with ochre and week of incubation as factors.

Source of Variation	DF	SS	MS	F	P
Ochre	4	164467.850	41116.963	2.545	0.105
Subject(Ochre)	10	161562.078	16156.208		
Week	1	316454.588	316454.588	23.567	<0.001
Ochre x Week	4	66255.039	16563.760	1.234	0.357
Residual	10	134276.232	13427.623		
Total	29	843015.788	29069.510		

429