9-2013

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Stephani A. Roman
Trinity College

William C. Johnson
University of Kansas Main Campus

Christoph Geiss
Trinity College, christoph.geiss@trincoll.edu

Geophysical Journal International

Geophys. J. Int. (2013) doi: 10.1093/gji/ggt349

Geophysical Journal International Advance Access published September 26, 2013

Grass fires—an unlikely process to explain the magnetic properties of prairie soils

Stephani A. Roman,[1] William C. Johnson[2] and Christoph E. Geiss[1,3]

[1] *Environmental Science Program, Trinity College,* 300 *Summit Street, Hartford, CT* 06106*, USA. E-mail: christoph.geiss@trincoll.edu*
[2] *The University of Kansas, Department of Geography,* 1475 *Jayhawk Blvd., Rm.* 213*, Lawrence, KS* 66045–7613*, USA*
[3] *Department of Physics, Trinity College,* 300 *Summit Street, Hartford, CT* 06106*, USA*

Accepted 2013 August 29. Received 2013 August 28; in original form 2013 May 17

SUMMARY

It has been proposed that grass fires affect the magnetic properties of soils by combining generally reducing soil conditions with elevated temperatures. To explore this supposition, we analysed surface and subsurface samples from loessic soils and compared their differences in magnetic properties as a function of fire intensity. Fire intensity was established based on types of burnt vegetation, which ranged from low-intensity fires in short-grass areas to high-intensity fires in tall-grass and forested areas. We measured low-field magnetic susceptibility (χ), a common proxy for the abundance of magnetic minerals, frequency-dependent susceptibility (χ_{FD}), a proxy for the presence of ultrafine-grained superparamagnetic minerals, and susceptibility of anhysteretic remanent magnetization (χ_{ARM}), a magnetic parameter highly dependent on the presence of fine, single-domain magnetic particles. Although intense fires led to an increase in frequency-dependent susceptibility and low-field magnetic susceptibility, moderately intense fires did not produce significant changes in magnetic properties. Observed magnetic changes are limited to sites that were very heavily burnt in forest areas. Grass fires are therefore an unlikely mechanism to explain a measurable component of the magnetic enhancement in prairie soils.

Key words: Environmental magnetism; Rock and mineral magnetism; North America.

1 INTRODUCTION

Magnetic properties of soils can serve as a proxy for various environmental conditions. In many instances the upper soil horizons are more magnetic than the underlying parent material (e.g. Le Borgne 1955), a process called magnetic enhancement. For example, the discovery of magnetic enhancement in soils on the Chinese Loess Plateau (CLP) allowed Kukla *et al*. (1988) to use magnetic susceptibility (χ) variations to delineate soil horizons and to reconstruct past climatic conditions from CLP loess-palaeosol sequences. Later studies identified increased concentrations of superparamagnetic (SP) and single domain (SD) magnetite (Fe_3O_4) or maghemite (γ-Fe_2O_3) particles as a cause of magnetic enhancement, which results in greater magnetic susceptibility values in the surface soil (A and B horizons) compared to subsurface horizons (C horizons; Maher 1986). Maher *et al*. (1994, 1995) subsequently used the degree of magnetic enhancement in CLP soils to reconstruct palaeorainfall and palaeomonsoon intensity. Similar techniques have been used elsewhere in Asia (Forster & Heller 1994) and North America (Geiss & Zanner 2007; Geiss *et al.* 2008).

Climate reconstructions using loessic soils in Europe found a more complex link between magnetic enhancement and climate (e.g. Oches & Banerjee 1996; Antoine *et al.* 2013). Studies of the magnetic properties in Alaskan loess soil were able to determine palaeowind intensity (e.g. Begét *et al.* 1990) and direction (Lagroix & Banerjee 2002). However, the magnetic properties of high-latitude loessic soils in Alaska and Siberia are reported to depend mainly on wind strength with magnetic enhancement being entirely absent or playing a minor role (e.g. Begét *et al.* 1990; Chlachula *et al.* 1998; Kravchinsky *et al.* 2008). While magnetic properties of soils continue to be used in palaeoclimate reconstructions, the causes of magnetic enhancement in soil are currently debated.

Over the years, several enhancement processes have been suggested. One of the initially proposed causes of magnetic enhancement in soils was the reduction of iron-bearing minerals during forest fires and subsequent oxidation to magnetite or maghemite (Le Borgne 1960). Later explanations established a possible fermentation mechanism, whereby organic matter decay in water saturated soils results in periods of reducing soil conditions, followed by oxidizing soil conditions when the soil dries out. In this process, hematite or other weakly magnetic iron-bearing minerals can be reduced to magnetite, which is then re-oxidized to maghemite (Mullins 1977). Based on this explanation, researchers developed

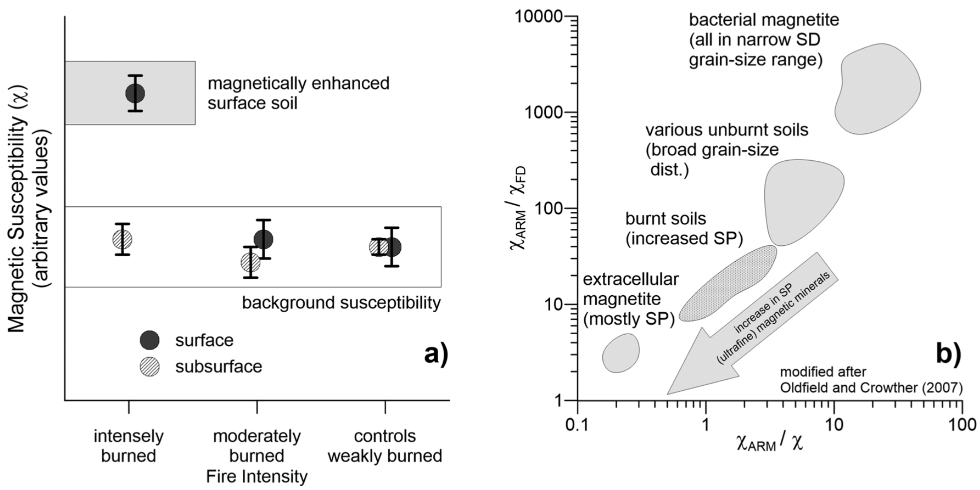

Figure 1. The expected magnetic signature of fire. (a) Changes in redox conditions combined with elevated temperatures lead to the formation of new ferrimagnetic phases. These additional magnetic minerals result in higher values of magnetic susceptibility (χ). This effect should be limited to the surface with subsurface samples remaining unaffected. (b) Newly formed magnetic phases are likely nanocrystalline and superparamagnetic. In a plot of χ_{ARM}/χ_{FD} versus χ_{ARM}/χ they should plot closer to the origin. Characteristic fields for various environments are taken from (Oldfield & Crowther 2007).

a growth model for magnetite that linked soil moisture and overall climate conditions to soil magnetic properties (Orgeira *et al.* 2011). Alternatively, Kukla (1988) proposed deposition of micrometeorites, strongly magnetic dust, or atmospheric fallout as a possible cause for magnetic enhancement, while Singer & Fine (1989) identified various other abiotic processes that can lead to magnetic enhancement. Other studies (e.g. Maher & Taylor 1988; Guyodo *et al.* 2006) suggested the neoformation of ferrimagnetic minerals such as magnetite and maghemite through a biologically mediated pathway.

The effects of fire on soil magnetic properties have also been further considered. While Le Borgne (1960) observed the effects of intense forest fires on soil magnetic properties, later studies used charcoal and magnetic properties of lake sediments to reconstruct the fire history in Yellowstone National Park (Whitlock & Millspaugh 1996). In a study of lake sediments from southern Switzerland, Gedye *et al*. (2000) employed a combination of charcoal counts and magnetic analyses to characterize the magnetic particles produced during forest fires as well as other weathering and soil-forming processes. They found that samples affected by fire (as determined by increased charcoal concentrations) contained higher concentrations of ferrimagnetic minerals and displayed magnetic particle size distributions (PSD) that were enriched in ultrafine SD particles. Oldfield & Crowther (2007) further investigated these changes in the abundance and PSD of fire-induced ferromagnetic minerals and found that soils affected by fire cluster tightly in a bivariate plot of χ_{ARM}/χ (susceptibility of anhysteretic remanent magnetization/low-field susceptibility) versus χ_{ARM}/χ_{FD} (susceptibility of anhysteretic remanent magnetization/frequency dependent susceptibility). Oldfield & Crowther (2007) show that such a combination of parameters can be used to distinguish the causes of magnetic enhancement in soils.

While the effect of intense fires on the magnetic properties on soils are well documented, the effects of less-intense fires and the minimum temperatures required for the neoformation of ferrimagnetic minerals is less clear. Rummery *et al.* (1979) detected evidence for past fires in lake drainage basins in north Wales and southwest France, and suggested that a minimum soil temperature of 400 °C, followed by a rapid cooling period was required for the formation of magnetic iron oxides. Other studies demonstrate that soil temperatures around 600 °C tend to produce peak susceptibility enhancement (Oldfield & Crowther 2007).

Based on a series of laboratory experiments, Kletetschka & Banerjee (1995) suggested that grass fires could be responsible for magnetic enhancement in soils on the CLP. If grass-fires produce significant magnetic enhancement, soil-magnetic parameters could then reflect the fire history for a given area. Changes in fire frequency and intensity depend on a balance between fuel availability and fuel moisture, and are therefore related to climatic conditions. While studies indicate that intense fire may produce magnetic enhancement in topsoil, few studies address whether grass fires reach maximum temperatures sufficient to cause the mineral transformations necessary for magnetic enhancement. The identification of a distinct magnetic signature of fire in soils will improve our understanding of the relations between pedogenic magnetic enhancement, fire and climate, and strengthen the interpretation of soil-magnetic properties as a climate proxy.

Heat and oxygen-poor conditions produced during intense fires can reduce weakly magnetic Fe-bearing minerals in the soil. While at elevated temperatures, these Fe-bearing mineral phases crystallize and form more strongly magnetic, ultrafine-grained ferrimagnetic minerals (Le Borgne 1955; Mullins 1977). This transformation process increases the magnetic susceptibility of the surface soil, which results in higher values of χ. Because many of these newly produced mineral phases contain poorly crystalline, ultrafine-grained SP minerals, soil samples affected by fire are characterized by a higher values of χ_{FD}. Fig. 1 shows the expected effects of intense fires on soil-magnetic properties. Intensely burnt sites should display higher susceptibility values in the topsoil (Fig. 1a) with the magnetic properties of lower soil horizons remaining unchanged. Furthermore, high concentrations of SP particles lead to higher χ_{FD} and χ values and relatively constant values of χ_{ARM}. Therefore, intensely burnt sites should plot closer to the origin in a graph of χ_{ARM}/χ_{FD} versus χ_{ARM}/χ (Fig. 1b; Oldfield & Crowther 2007). Moderate grass fires, which might not reach the necessary temperatures or may not last long enough to cause significant mineral transformations, are not expected to alter the magnetic properties in soil. At this point, however, the threshold between ‘intense’ and 'moderate' fires with respect to fire-induced magnetic enhancement remains poorly defined.

The frequency of fire may also have implications for fire history studies and climate reconstruction modelling. Recent studies (Blake *et al.* 2006) found no clear 'memory' of previous fires in long, unburnt soils from areas known to have been affected by fire in the past. At this point, whether any fire-induced signal would persist over time and significantly contribute to the long-term soil magnetic properties has not been determined. If fire does produce persistent changes in the magnetic properties of the soil, areas that are frequently burnt should have elevated magnetic properties indicative of fire.

In this study, we analyse the magnetic properties of soils that developed in grasslands and oak savanna and that were subjected to a series of prescribed burns. This analysis will allow us to answer the following questions: are grassland fires intense enough to cause magnetic enhancement in soils, and, if present, does a fire-induced magnetic signature build up over time and is it affected by the frequency of fire over time?

Table 1. Criteria to estimate fire intensity.

Fire intensity	Corresponding fuel conditions	Sites
1	Unburnt controls	HBR 11-A Transect HBR 11-D HNC 11-A, B
2	Short grass, mowed	Transect HBR 11-D
3	Short seasonal grasses, dry	HBR 11-B Transect HBR 11-D Transect HBR 11-D
4	Tall seasonal grasses, dry Leaf litter	HBR 11-A HBR 11-C HBR 11-H HNC 11-A, B
5	Cedar trees	HBR 11-C Transect HBR 11-D
6	Long, intense fires under toppled trees, slash piles	HBR 11-A Transect HBR 11-D

2 STUDY SITES

2.1 Hitchcock Nature Center, Iowa

The first group of study sites is located at the Hitchcock Nature Center (HNC) in Honey Creek, Iowa (41°01′N, –95°09′W). HNC consists of 1268 acres (513 ha) of land located in the Loess Hills of Western Iowa, which consist of finely ground windblown loess deposited 20 000–10 000 years ago. Today, the average annual total precipitation is approximately 790 mm. During the winter months, temperatures range from –6 to –3 °C. The spring season average temperatures range from 7 to 23 °C. Summer temperatures average between 22 and 24 °C with some high temperature extremes above 38 °C. The vegetation at HNC is comprised of dry loess prairie, oak savanna and mesic oak woodlands. The Natural Areas Management (NAM) regulates the area and supports a natural fire regime that annually burns parcels of the property to thin woodlands and promote the growth of native species. Soils (Hamburg silt loam, mesic typic Udorthent) form on steep to moderately steep slopes (40–70 per cent) and are poorly developed due to high erosion rates. Therefore, it should be possible to observe the effects of single fire events against a relatively poorly developed magnetic background signal. Estimates of fire intensity for each site are based on pre-existing vegetation and amount of leaf litter present at the time of a prescribed burn. In some instances maximum ground temperatures were measured directly through the use of temperatures sensitive paints as described later. The criteria used to estimate fire intensity are listed in Table 1. Soil samples were analysed from the following sites (Fig. 2):

(i) HBR11A is near the crest of a loess ridge in oak savanna. Samples were collected around a burnt, toppled tree and in unburnt area nearby. Heaviest fire intensity was observed directly under a burnt tree trunk.

(ii) HBR11B is located on a narrow ridgeline and covered by short grass. No unburnt controls were collected from this site.

(iii) All of samples from HBR11C site were collected near an intensely burnt cedar forest at the base of a loess ridge. Cedar trees were still standing upright after the fire. Vegetation between trees consisted of tall grasses.

(iv) HBR11D is located on the foot slope of a loess ridge and samples along a gradient of vegetation types and fire intensity. The transect begins in dense and intensely burnt cedar forest, crosses moderately burnt tall-grass vegetation, and ends in unburnt pasture.

(v) HBR11H is located on the foot slope of a loess ridge in cedar forest and tall grass prairie. Soils were sampled in varying proximity to burnt cedar trees, and we assigned the entire site an intensity intermediate between cedar forests and tallgrass prairie.

(vi) HNC11A and B are situated at the foot slope of a loess ridge. The prescribed fire at this site did not affect the entire slope and control samples were collected from unburnt patches next to burnt soil and vegetation. Vegetation consisted of tall grasses and brush.

2.2 Konza Prairie, Kansas

Konza Prairie is located in the Flint Hills of central Kansas (39°05′N, –96°36′W) and is managed as a long-term ecological research (LTER) site by Kansas State University and The Nature Conservancy. Upland soils (Clime – Sogn complex, mesic udorthentic Haplustolls) formed in thin loess that mantles bedrock consisting of primarily cherty limestone and shale. Broad-topped ridges of the study site limit erosion and allow for stable soils. Konza Prairie experiences a mean annual precipitation of 835 mm. Average temperatures range between –9 and 33 °C. Tall grasses covered all plots studied. The area was chosen because it has a long-term history of controlled burns. Most prescribed burns occur in the spring, and burn intervals range from annually to as long as 20 yr. Fig. 3 shows the location of all sampling sites and indicates burn frequencies. All soil cores were sampled on broad, stable ridge tops with slopes <1 per cent.

3 METHODS

3.1 Sampling

At Hitchcock Nature Center, surface and subsurface soils were sampled at selected locations before and after prescribed burns. Since the effect of modest fires are limited to the soil surface (Monson *et al.* 1974; Raison *et al.* 1986; Iverson & Hutchinson 2002) the potential effects of fire are strongest at the very surface. We therefore collected surface samples which consisted of the uppermost centimetre of the soil horizon, and compared these to subsurface samples, which were collected between 3 and 10 cm

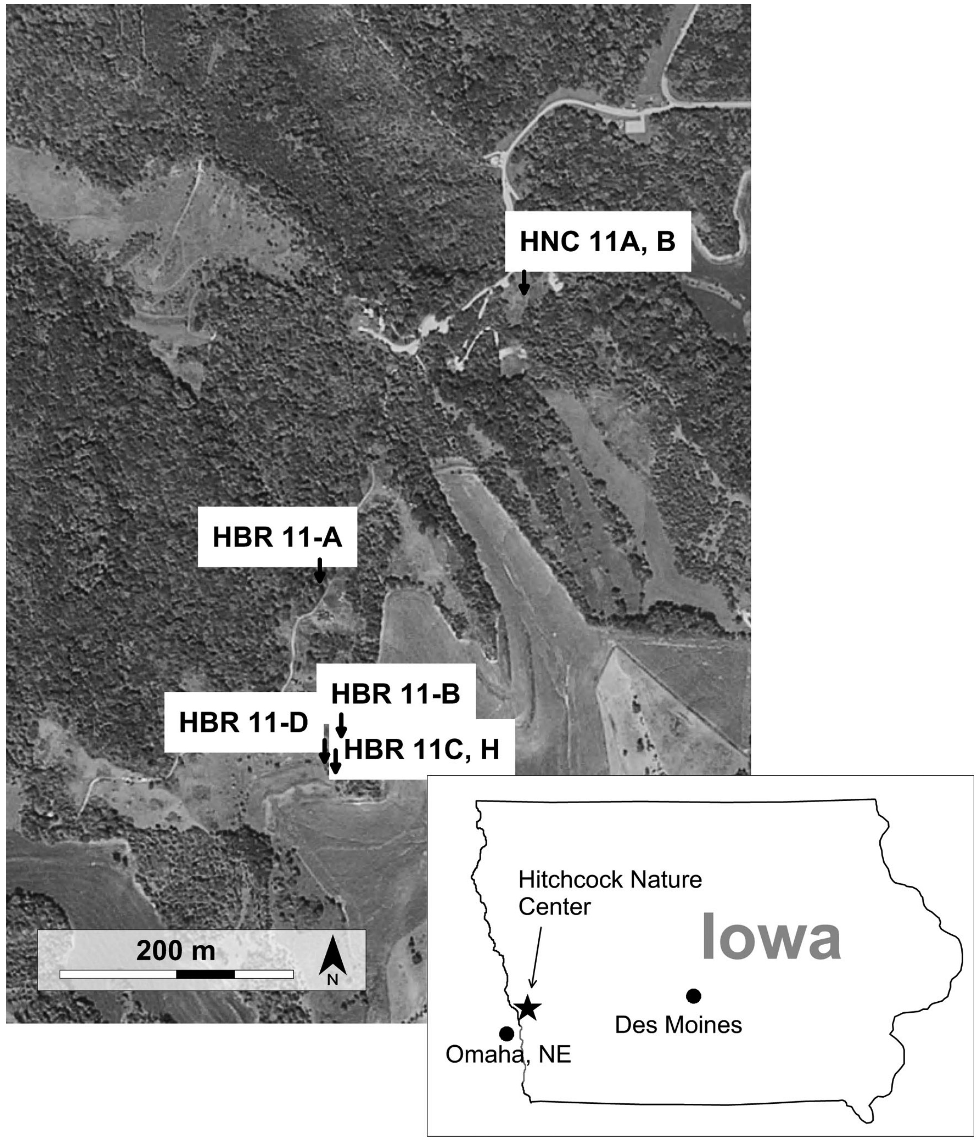

Figure 2. Sitemap of Hitchcock Nature Center (HNC), Honey Creek Iowa. (aerial image: courtesy of HNC).

depth. These subsurface samples have magnetic properties similar to unaltered Peoria loess from the same area (Geiss unpublished data) and its magnetic properties are unlikely to be affected by past fires. At Konza Prairie, short cores were obtained with a manually operated, 1.5 inches (3.8 cm) diameter soil core sampler (AMS Inc.). Cores were air-dried and subsampled at 1 cm intervals. Only the uppermost surface samples (0–2 cm) were used for this study.

3.2 Measurements

Low-field magnetic susceptibility (χ, same as low-frequency susceptibility χ_{lf} when calculating χ_{FD}), which serves as a proxy for the concentration of all magnetic minerals, was measured using an AGICO KLY-4 (Kappabridge) susceptibility meter. Frequency-dependent magnetic susceptibility ($\chi_{\mathrm{FD}} = \chi_{\mathrm{lf}} - \chi_{\mathrm{hf}}$) is used to estimate the abundance of ultrafine SP minerals ($d \ll 0.1$ μm) and was measured at 470 Hz (for χ_{lf}) and 4.7 kHz (for χ_{hf}) using a Bartington MS2B sensor. Each measurement used an averaging time of 10 s, and measurements were repeated five times for each sample. Susceptibility of Anhysteretic Remanent Magnetization (χ_{ARM}) provides a measure of fine, single-domain (SD) minerals (0.1 μm $< d <$1 μm). An anhysteretic remanence was applied using a Magnon International AFD 300 alternating field demagnetizer (bias field: 50 μT, peak alternating field: 100 mT) and measured using an AGICO JR6 spinner magnetometer. Values of χ_{ARM} were calculated from Anhysteretic Remanent Magnetization (ARM) by normalizing ARM by the bias field.

The thermal stability of loess samples was investigated by heating several mixtures of loess and ground sugar to simulate the presence of organic matter in the topsoil (Hanesch *et al.* 2006) in the furnace attachment of the KLY-4 susceptibility meter. Susceptibility changes were continuously monitored during the heating and cooling process, and every sample was heated only once. Subaerial heating was approximated by flushing the furnace tube with compressed air (flow-rate 20 ml min^{-1}) during the experiment. At selected sites, we estimated peak soil temperatures during fires by coating small aluminum plates with patches of heat sensitive paints (Tempilaq® temperature indicating liquid) that have well-defined melting points between 200 and 1500 °F (93 and 816 °C). These plates were placed

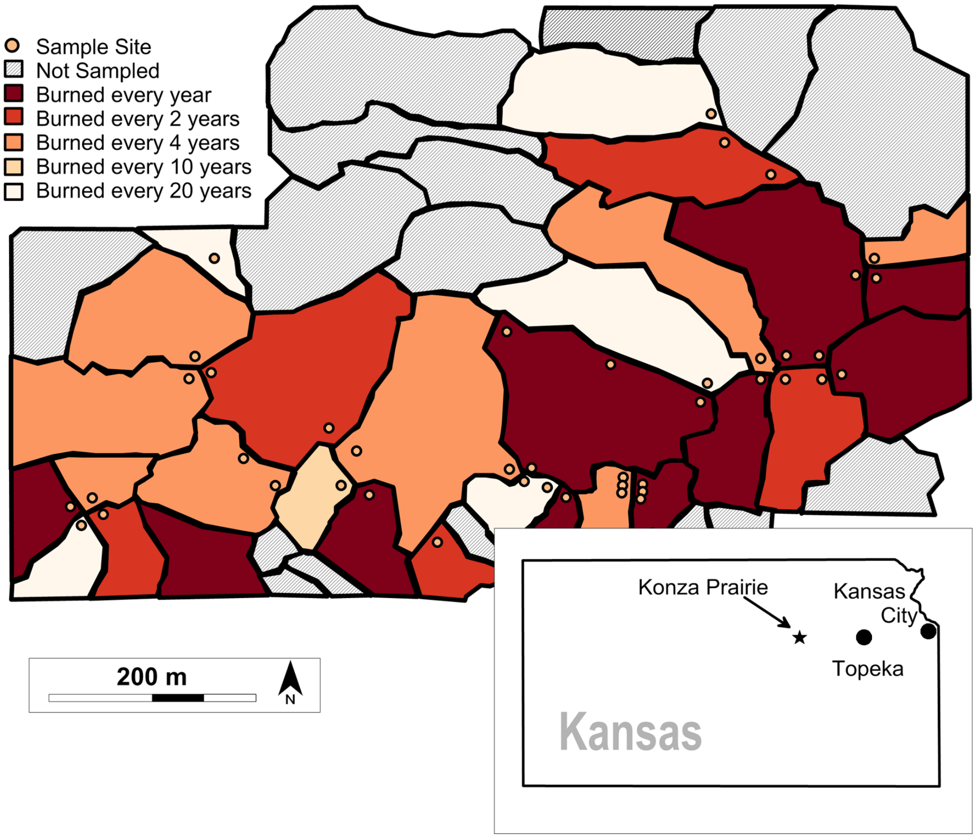

Figure 3. Site map of Konza Prairie, Kansas.

at our sampling sites prior to a controlled burn, and maximum burn temperatures were estimated by identifying the molten colour patch with the highest melting temperature.

Intensely burnt soils were studied to determine if intense fire produces a distinctive magnetic signal as suggested by Oldfield & Crowther (2007). Moderately burnt grassland and oak-woodland soils were investigated to determine if these fires burn hot enough to produce a magnetic signature characteristic of fire. Results from these controlled burns were also compared to the magnetic properties of a well-developed grassland soil. Samples from Konza Prairie allowed for the investigation of grassland soils that have been burnt at various frequencies (ranging between annually to once every 20 yr). Data from these sites enabled us to examine any long-term cumulative effect of grassland fires. All magnetic results are summarized in Tables 2 (Hitchcock nature Center) and 3 (Konza Prairie).

4 RESULTS AND DISCUSSION

The magnetic properties of surface soils collected along a transect of intensely burnt to unburnt controls (site HBR11D) are shown in Fig. 4. Intensely burnt surface samples located within the burnt cedar grove are magnetically enhanced relative to the parent material in the subsoil and exhibit higher values of χ (Fig. 4a and Table 2). Moderately burnt samples and unburnt controls show no significant change in χ with respect to the subsurface, indicating that no mineral transformations have occurred. Magnetic mineral grain size varies between intensely burnt and unburnt controls. Intensely burnt samples have a higher concentration of SP particles and plot closer to the origin in a plot of $\chi_{\mathrm{ARM}}/\chi_{\mathrm{FD}}$ versus χ_{ARM}/χ (Fig. 4b) than moderately burnt sites and unburnt controls. These intensely burnt surface soil samples have $\chi_{\mathrm{ARM}}/\chi_{\mathrm{FD}}$ and χ_{ARM}/χ ratios that are similar to burnt soils analysed by Oldfield & Crowther (2007), which are shown as black crosses in Fig. 4(b). As fire intensity increased, the abundance of ultrafine-grained SP particles increased.

An intensely burnt site near the top of Badger Ridge (HBR11A) provides further evidence that intense fires can cause magnetic enhancement and affect the magnetic properties of the surface soil. Samples taken from directly beneath a toppled log where fire produced elevated temperatures are characterized by an increase in the magnetic susceptibility relative to the parent material (Fig. 5a and Table 2) and have the highest abundance of SP particles (Fig. 5b). These samples plot directly in the field delineated by Oldfield & Crowther (2007) for burnt soils. Samples taken from below the toppled tree, but away from the trunk (intensity 5) revealed moderate increases in χ and slight enrichment in SP particles relative to unburnt controls. Our analysis from these two sites (HBR 11-A and 11-D) indicated that intense fires in our study area cause magnetic enhancement in loessic soils and lead to a specific set of magnetic properties (high surface χ, low χ_{ARM}/χ and $\chi_{\mathrm{ARM}}/\chi_{\mathrm{FD}}$) which can be used to identify fire as a cause of magnetic enhancement.

At all sites moderately burnt samples do not, however, show significant changes in magnetic properties relative to the parent material (Fig. 6a and Table 2). Moderately burnt samples (intensity 1–4) have χ-values similar to the subsurface and do not display the increase in SP abundance that characterizes intensely burnt sites. The magnetic mineral grain size of moderately burnt samples is well outside the parameter range for burnt soils as outlined by Oldfield and Crowther and overlaps significantly with that of unburnt control samples (Fig. 6b). The magnetic properties of these sites are similar to those of the subsoil and unburnt controls. Therefore, the

Table 2. Magnetic data for Hitchcock nature area sites.

Sample	Int.	χ_{ARM}	χ (χ_{lf}) (10^{-6} m^3 kg^{-1})	χ_{hf}	χ_{ARM}/χ	χ_{ARM}/χ_{FD}
HBR11D-1 SF	6	3.04	1.13	1.07	2.7	55
HBR11D-2 SF	5	3.35	1.25	1.18	2.7	48
HBR11D-3 SF	4	1.83	0.58	0.56	3.1	64
HBR11D-4 SF	4	1.78	0.59	0.57	3.0	92
HBR11D-5 SF	3	1.76	0.57	0.55	3.1	98
HBR11D-6 SF	1	1.82	0.54	0.53	3.4	135
HBR11D-7 SF	1	1.80	0.54	0.53	3.3	165
HBR11D-1 SSF		1.70	0.59	0.58	2.9	165
HBR11D-2 SSF		1.98	0.61	0.60	3.2	156
HBR11D-3 SSF		1.93	0.58	0.56	3.4	129
HBR11D-4 SSF		2.30	0.59	0.59	3.9	261
HBR11D-5 SSF		1.75	0.61	0.60	2.9	115
HBR11D-6 SSF		1.99	0.57	0.56	3.5	171
HBR11D-7 SSF		1.88	0.60	0.59	3.1	157
HBR 11A-1 SF	5	3.54	1.13	1.06	3.1	53
HBR 11A-2 SF	5	3.04	0.97	0.92	3.1	63
HBR 11A-3 SF	5	3.77	1.29	1.21	2.9	43
HBR 11A-4 SF	5	3.22	1.04	0.98	3.1	57
HBR 11A-5 SF	5	4.06	1.10	1.04	3.7	69
HBR 11A-1 SSF		3.71	0.81	0.78	4.6	113
HBR 11A-2 SSF		2.24	0.78	0.75	2.9	83
HBR 11A-3 SSF		2.25	0.75	0.71	3.0	73
HBR 11A-4 SSF		2.94	0.78	0.76	3.8	111
HBR 11A-5 SSF		3.70	0.85	0.82	4.3	117
HBR 11A-6 SF	1	2.97	0.80	0.77	3.7	101
HBR 11A-7 SF	1	1.96	0.67	0.65	2.9	68
HBR 11A-8 SF	1	2.62	0.67	0.65	3.9	141
HBR 11A-9 SF	1	2.40	0.71	0.69	3.4	125
HBR 11A-10 SF	1	2.58	0.70	0.67	3.7	87
HBR 11A-6 SSF		4.48	0.80	0.77	5.6	144
HBR 11A-7 SSF		2.83	0.77	0.74	3.7	100
HBR 11A-8 SSF		2.26	0.68	0.66	3.3	89
HBR 11A-9 SSF		3.11	0.75	0.72	4.1	103
HBR 11A-10 SSF		0.00	0.71	0.69		
HBR 11A-11	6	11.77	5.58	5.15	2.1	27
HBR 11A-12	6	12.06	6.07	5.63	2.0	28
HBR 11A-13	6	2.43	0.82	0.79	2.9	77
HBR 11A-14	6	2.04	0.76	0.73	2.7	63
HBR 11B-1 SF	3	2.97	0.60	0.58	5.0	148
HBR 11B-2 SF	3	3.38	0.66	0.63	5.2	111
HBR 11B-3 SF	3	5.55	0.75	0.72	7.4	161
HBR 11B-4 SF	3	3.13	0.62	0.60	5.0	130
HBR 11B-5 SF	3	3.37	0.67	0.64	5.1	120
HBR 11C-1 SF	5	4.88	1.16	1.11	4.2	90
HBR 11C-2 SF	5	5.02	1.03	0.98	4.8	94
HBR 11C-3 SF	5	8.30	1.32	1.24	6.3	101
HBR 11C-4 SF	5	6.03	1.42	1.35	4.3	85
HBR 11C-5 SF	5	7.36	1.75	1.65	4.2	80
HBR 11C-1 SSF		3.10	0.68	0.66	4.5	164
HBR 11C-2 SSF		3.48	0.73	0.72	4.8	223
HBR 11C-3 SSF		3.22	0.72	0.70	4.5	177
HBR 11C-4 SSF		3.24	0.70	0.69	4.6	211
HBR 11C-5 SSF		3.42	0.75	0.73	4.6	229
HBR 11H-1 SF	4	2.23	0.84	0.81	2.7	93
HBR 11H-2 SF	4	1.80	0.63	0.61	2.9	129
HBR 11H-3 SF	4	2.93	1.26	1.20	2.3	56
HBR 11H-1 SSF		1.81	0.67	0.65	2.7	85
HBR 11H-2 SSF		1.70	0.56	0.55	3.1	183
HBR 11H-3 SSF		1.94	0.71	0.69	2.7	97
HNC 11A-1 SF	1	1.90	0.54	0.52	3.5	98
HNC 11A-2 SF	1	1.95	0.54	0.51	3.6	72
HNC 11A-3 SF	1	1.00	0.38	0.37	2.6	95
HNC 11A-4 SF	4	1.34	0.44	0.43	3.1	162
HNC 11A-5 SF	4	1.61	0.48	0.46	3.4	142
HNC 11A-6 SF	4	1.87	0.56	0.52	3.4	48
HNC 11A-1 SSF		1.83	0.50	0.49	3.6	118
HNC 11A-2 SSF		1.87	0.54	0.53	3.4	106
HNC 11A-3 SSF		0.92	0.37	0.36	2.5	162
HNC 11A-4 SSF		1.33	0.43	0.43	3.1	140
HNC 11A-5 SSF		1.90	0.56	0.53	3.4	59
HNC 11A-6 SSF		1.87	0.57	0.55	3.3	116
HNC 11B-1 SF	1	2.08	0.62	0.60	3.4	135
HNC 11B-2 SF	1	2.09	0.69	0.68	3.0	162
HNC 11B-3 SF	1	1.82	0.58	0.57	3.1	162
HNC 11B-4 SF	4	2.11	0.61	0.59	3.4	106
HNC 11B-5 SF	4	2.02	0.58	0.56	3.5	102
HNC 11B-6 SF	4	2.10	0.61	0.58	3.5	88
HNC 11B-1 SSF		2.04	0.63	0.61	3.3	123
HNC 11B-2 SSF		2.02	0.78	0.77	2.6	245
HNC 11B-3 SSF		1.92	0.61	0.59	3.1	90
HNC 11B-4 SSF		1.93	0.60	0.59	3.2	141
HNC 11B-5 SSF		1.90	0.60	0.58	3.2	152
HNC 11B-6 SSF		1.80	0.59	0.58	3.0	127

magnetic properties of moderately burnt surface soils appear unaltered by fire.

Fig. 6(b) also compares the previously discussed samples to a well-developed and strongly magnetically enhanced grassland soil from central Nebraska (site 4G 99, Geiss *et al.* 2004). This soil (solid triangles in Fig. 6b) contains fewer SP-sized minerals, and all samples plot in the upper right of Fig. 6(b), in a region clearly separate from intensely burnt sites. As the samples from moderately burnt sites, unburnt controls, and a nearby well-developed and strongly magnetically enhanced soil are similar in their magnetic mineral grain-size distribution, the effects of grassland fires on soil-magnetic properties appear to be small to non-existent. The heat produced in these moderately intense fires is unlikely to produce the required temperature or duration of heat exposure necessary to alter the magnetic mineralogy in the surface soil. Therefore, moderate fires are unlikely to play a significant role in the magnetic enhancement of Midwestern grass-land soils. This is contrary to previous research that suggests grass fires may affect the magnetic properties of similar soils on the CLP (Kletetschka & Banerjee 1995).

Experimental data of soil heated with sugar (to simulate organic matter accumulation in the topsoil) to various temperatures show that a significant, irreversible increase in magnetic susceptibility

Table 3. Magnetic data for Konza Prairie sites.

Site	Burn freq.	Lat.	Long.	χ_{ARM}	χ (χ_{lf}) (10^{-6} m^3 kg^{-1})	χ_{hf}	χ_{ARM}/χ	χ_{ARM}/χ_{FD}
A1	1	39.09061	−96.55302	7.02	0.95	0.89	7.39	123
A2	4	39.09084	−96.55306	7.83	1.07	0.97	7.29	75
A3	1	39.09043	−96.55490	8.54	1.20	1.10	7.09	80
B1	2	39.08370	−96.55619	2.98	0.44	0.41	6.74	97
B2	1	39.08397	−96.55621	6.02	0.66	0.61	9.07	107
B3	1	39.08340	−96.55520	4.55	0.60	0.59	7.55	263
C1	2	39.08373	−96.55913	1.68	0.39	0.36	4.36	60
C3	4	39.08491	−96.55995	7.03	0.90	0.88	7.77	268
D1	20	39.08190	−96.56395	5.73	0.94	0.85	6.10	68
D2	1	39.08160	−96.56420	5.24	0.80	0.77	6.52	155
D3	1	39.08204	−96.56217	7.49	1.13	1.06	6.63	105
E1	4	39.07538	−96.56945	9.25	1.23	1.13	7.54	95
E2	1	39.07513	−96.56901	8.52	1.21	1.13	7.07	120
E3	1	39.07513	−96.56901	8.14	1.25	1.15	6.51	80
E4	1	39.07504	−96.56929	8.70	1.31	1.18	6.63	64
E5	4	39.07479	−96.56929	9.01	1.22	1.12	7.41	95
E6	4	39.07479	−96.56929	9.54	1.31	1.18	7.29	75
F1	1	39.07441	−96.57405	4.63	0.64	0.59	7.22	83
G1	20	39.07540	−96.57688	9.08	1.10	0.97	8.22	66
G2	4	39.05773	−96.57700	6.73	0.90	0.86	7.51	170
G3	1	39.07580	−96.57674	7.76	1.11	1.00	7.00	71
I1	1	39.07486	−96.58790	4.42	0.66	0.60	6.70	78
I2	10	39.07497	−96.58840	4.92	0.64	0.54	7.63	47
J1	4	39.07767	−96.58939	6.92	1.01	0.91	6.84	69
J2	2	39.07862	−96.59025	6.85	1.06	0.99	6.44	91
J3	10	39.07862	−96.59025	6.37	0.79	0.72	8.06	91
K1	4	39.07666	−96.59521	6.68	1.06	0.94	6.33	58
L1	1	39.07318	−96.60685	9.01	1.28	1.15	7.03	67
L2	20	39.07293	−96.60669	9.32	1.45	1.33	6.42	78
L3	2	39.07289	−96.60648	9.11	1.06	0.97	8.62	110
L4	4	39.07323	−96.60661	9.55	1.41	1.27	6.80	73
M2	4	39.08348	−96.59958	8.10	0.92	0.82	8.85	84
M3	4	39.08348	−96.59958	8.48	1.25	1.15	6.76	83
N1	20	39.09147	−96.59836	7.55	1.05	1.00	7.17	156
O1	20	39.08653	−96.57286	8.99	1.06	0.87	8.51	47
O2	20	39.08351	−96.56706	7.98	0.91	0.90	8.77	968
P1	2	39.09860	−96.55900	1.85	0.45	0.41	4.14	56
Q1	2	39.10151	−96.56302	4.45	0.81	0.71	5.50	46
Q2	20	39.10168	−96.56303	6.00	0.88	0.77	6.79	55

occurs only at temperatures above 275 °C (Fig. 7). Samples that reached maximum temperatures <225 °C did show an increase in magnetic susceptibility during heating, but this change was reversible and is likely due to thermal unblocking of single-domain particles. Temperature data from six of our burnt sites indicate that moderate fires did not reach ground temperatures above 250–300 °F (120–150 °C), well below the temperatures needed for the neoformation of magnetic minerals. The maximum-recorded ground temperature of 400 °F (205 °C) occurred at HNC 11A, a site with dense tall-grass vegetation. This site did not show any magnetic enhancement signal.

Samples from Konza Prairie (Fig. 8, Table 3) demonstrate the effects of various burn frequencies and persistence of magnetic property changes. No correlation was found between the magnetic susceptibility of surface samples and the frequency with which they were subjected to prescribed burns (Fig. 8a). Surface samples from sites that have been burnt annually have similar magnetic mineral grain size to sites burnt every 10–20 yr (Fig. 8b). Burn frequency and magnetic mineral grain size were not correlated. Three samples from annually burnt sites plot near the region of burnt soils provided by Oldfield & Crowther (2007), but most others do not follow the trend. Our analysis suggests that the frequency of fire does not affect the magnetic susceptibility and magnetic grain size distribution of grassland soils. Ongoing long-term studies of recently burnt sites will clarify whether most fires in our study region are simply not intense enough, or whether the fire-induced magnetic signal does not persist over time.

By following the method of Oldfield & Crowther (2007) we characterize the abundance of ultrafine SP particles in the magnetically enhanced soil horizons. Our analysis of sites HBR 11-A and HBR 11-D (Fig. 4) shows that this approach is valid, and heavily burnt soils are indeed enriched in SP particles. We would like to point out that this method makes no assumption about the mineralogy of this new-formed phase. Our thermal experiments suggest the neoformation of magnetite or maghemite from some other Fe-bearing phase. This agrees with several other recent studies (Nørnberg *et al.* 2009; Clement *et al.* 2011) which detect the conversion of weakly magnetic iron-minerals to maghemite during natural and prescribed

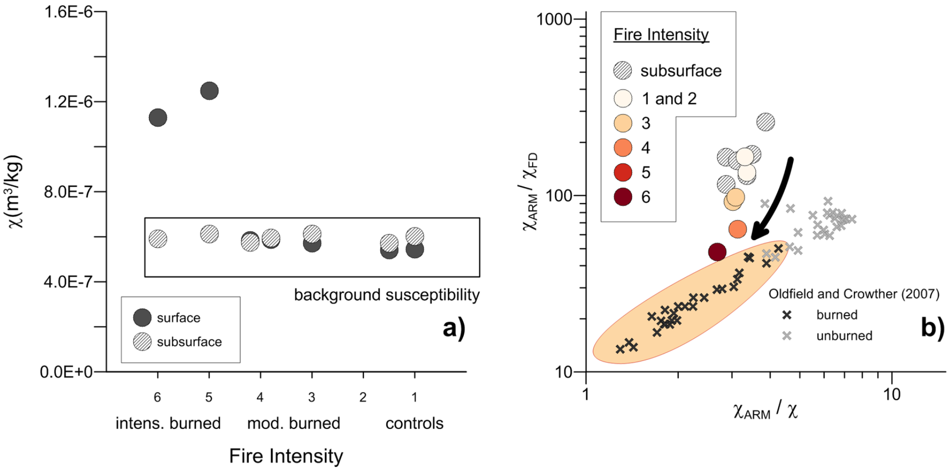

Figure 4. Magnetic enhancement along transect HBR 11-D. (a) Intensely burnt samples in cedar forest and under toppled trees show higher values of magnetic susceptibility, while moderately burnt samples have magnetic susceptibility values similar to unburnt controls and subsurface material. (b) Intensively burnt samples display higher concentrations of SP particles, plotting progressively closer to the origin in a bivariate plot of χ_{ARM}/χ_{FD} versus χ_{ARM}/χ. The most intensely burnt samples plot closely to the region of burnt soils identified by Oldfield & Crowther (2007) indicated by grey crosses.

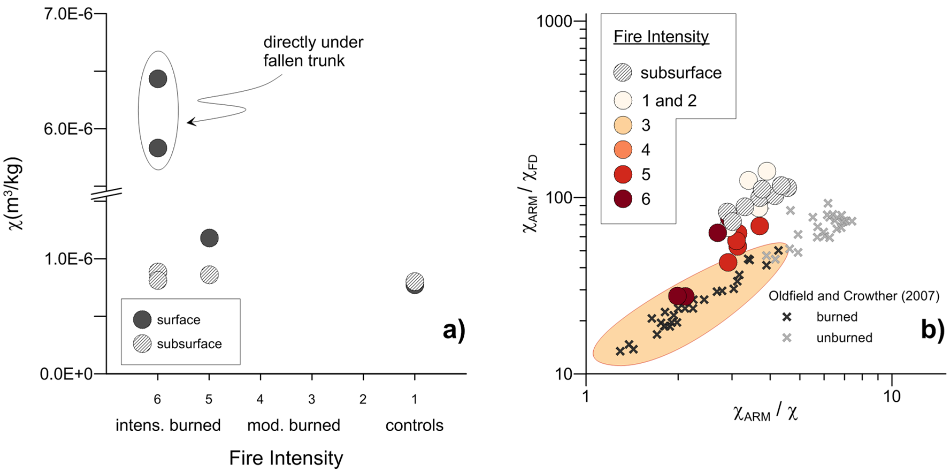

Figure 5. Fire-induced magnetic enhancement in site HBR 11-A. (a) Significant increases in magnetic susceptibility are only observed for intensely burnt samples that experienced high temperatures under a toppled tree. (b) These samples plot within the envelope of burnt soils outlined by Oldfield & Crowther (2007) (Oldfield & Crowther 2007).

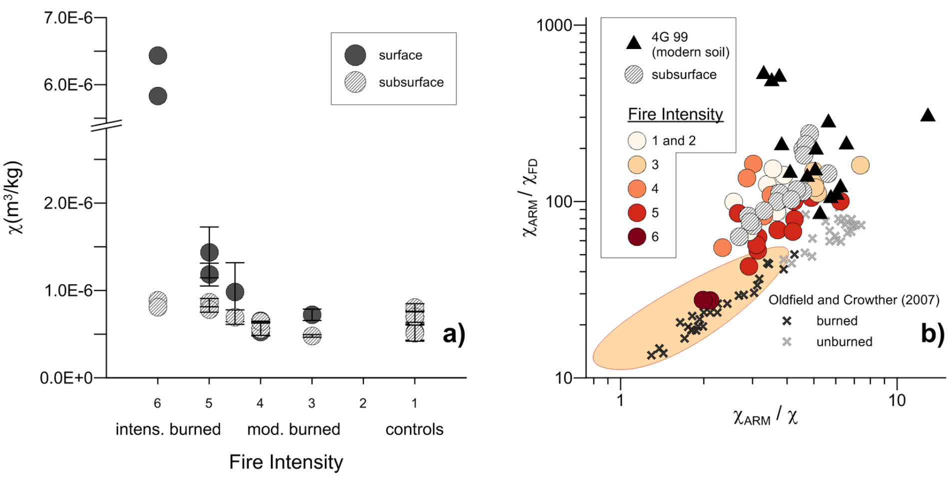

Figure 6. Magnetic properties of all analysed samples. (a) Only intensely burnt samples are characterized by significant increases in susceptibility. (b) Most of these samples show only small increases in SP grains and plot in a region that overlaps with unburnt soil sites from Oldfield & Crowther (2007) (Oldfield & Crowther 2007) but distant from burnt soils. Solid crosses indicate samples from a well-developed soil in Nebraska. None of these samples has magnetic properties that are indicative of burning.

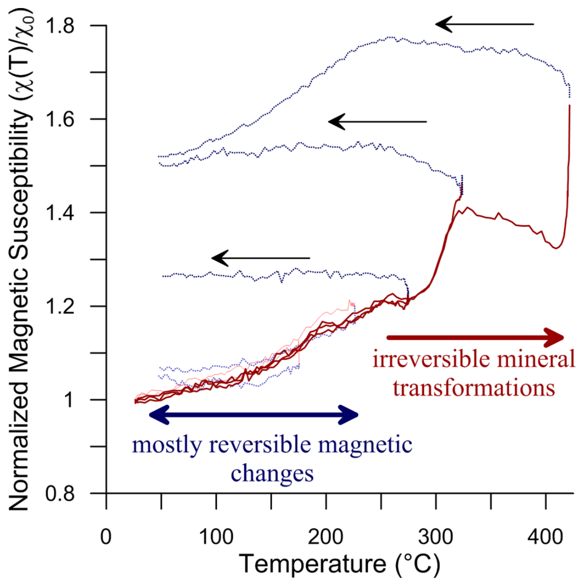

Figure 7. Variations in magnetic susceptibility with temperature for a series of loess samples. Samples were mixed with ground sugar to simulate the organic matter content of the topsoil. Samples were heated under a flow of compressed air (flow rate 20 ml min^{-1}). Irreversible magnetic mineral transformations require the samples to be heated above 250 °C.

forest fires. Clement *et al.* use IRM acquisition curves to detect changes in magnetic coercivity and hence magnetic mineralogy. This approach suggests that magnetic enhancement at their study sites is due to the addition of (slightly) larger, remanence-carrying grains. In most cases, including our and previous studies, the magnetically enhanced soil horizons are characterized by the addition of both SP (Geiss *et al.* 2004; Machac *et al.* 2007) and remanence carrying grains (Geiss *et al.* 2004; Geiss & Zanner 2006).

Our study also shows relatively modest magnetic enhancement after forest fires, which is seemingly in contradiction with other studies (e.g. Le Borgne 1955; Rummery *et al.* 1979; Ketterings *et al.* 2000; Blake *et al.* 2006; Oldfield & Crowther 2007). It should be pointed out that the investigated forested sites are covered by oak savanna which, in prehistoric times, burned frequently (Stambaugh *et al.* 2006). Such frequent fires may have kept fuel loads low and may have resulted in numerous low-intensity fires that did not cause significant magnetic enhancement. Such an interpretation is supported by Iverson & Hutchinson (2002) who observed only short (few minutes) and modest increases in soil temperature ($\Delta T_{max} = +10\,°C$ at 1 cm depth) for prescribed burns in mixed oak forests.

5 CONCLUSIONS

Magnetic enhancement in soil is correlated with fire intensity, and intense fire does magnetically enhance soil. Fire-induced magnetic enhancement results in an increase in the abundance of ultrafine grained, SP minerals. These changes lead to increased values of low-field magnetic susceptibility χ, which tracks the overall increase in ferrimagnetic minerals and to low ratios of χ_{ARM}/χ and χ_{ARM}/χ_{FD}, which reflect the nanocrystalline nature of these newly formed magnetic phases. These changes were limited to soils that experienced the intense heat caused by burning trees and brush.

Moderately intense grass fires have little to no effect on the magnetic properties of the surface soil. These fires, typical of the prairies in the Midwestern United States, do not produce a distinct magnetic signature. A well-developed and strongly magnetically enhanced loessic soil from Nebraska displayed magnetic properties characteristic of unburnt soils. As a result, the often-complicated relationships between fire, climate and soils do not have to be taken into account when using the magnetic properties of palaeosols as climatic archives.

The persistence of the magnetic mineral property changes caused by grass fires is unclear, but frequently burnt prairie soils do not differ from rarely burnt similar sites in their magnetic properties. In general, grass fires are an unlikely mechanism for magnetic enhancement in prairie soils.

ACKNOWLEDGEMENTS

We thank the staff of Hitchcock Nature Center for years of continued support especially Chad Graeve, the Pottawattamie County Natural Resource Specialist. We also thank Kansas State University for access to and permission to sample Konza Prairie. We appreciate the assistance of Giuliani Lopez and Brittney Payton in sampling soil cores at Konza Prairie and analysing samples. Two anonymous reviews greatly improved the manuscript. The project was funded by grants from Trinity College's Faculty Research Committee. CEG's laboratory facilities were sup-

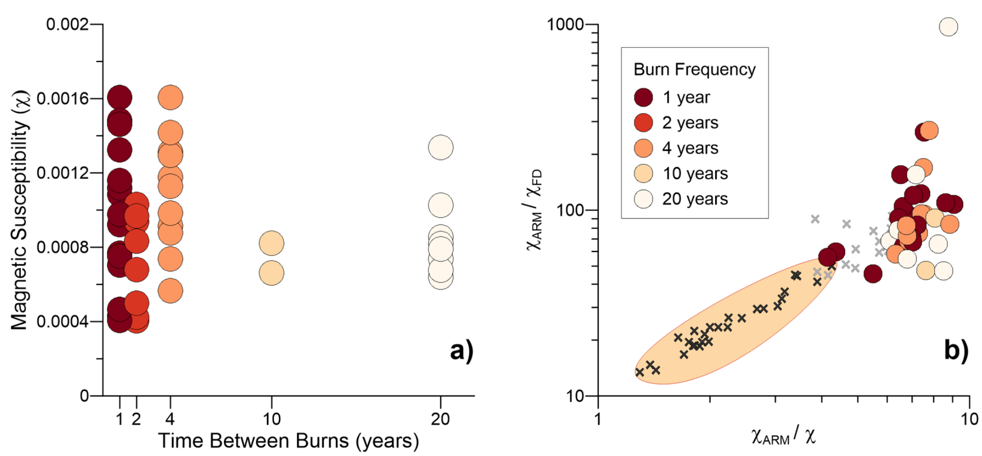

Figure 8. Magnetic properties of surface soil samples from Konza Prairie. (a) magnetic susceptibility (χ) shows no systematic correlation with burn frequency (b) and there is no systematic increase in the abundance of superparamagnetic (SP) particles.

ported by NSF grants EAR-MRI 0320976, EAR-MRI 0923043 and CHE-MRI 0959526.

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