EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms (2010)

Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.2060

The effects of wildfires on the magnetic properties of soils in the Everglades

Bradford M. Clement,[1]* Jose Javier,[2] Jay P. Sah[3] and Michael S. Ross[2,3]
[1] Integrated Ocean Drilling Program and Department of Geology and Geophysics, Texas A&M University, College Station, TX, USA
[2] Department of Earth & Environment, Florida International University, Miami, FL, USA
[3] Southeast Environmental Research Center, Florida International University, Miami, FL USA

Received 30 July 2009; Revised 4 June 2010; Accepted 15 June 2010

*Correspondence to: Bradford M. Clement, Integrated Ocean Drilling Program and Department of Geology and Geophysics, Texas A&M University, College Station, TX 77845, USA. E-mail: clement@iodp.tamu.edu

ESPL
Earth Surface Processes and Landforms

ABSTRACT: We present results of a rock-magnetic study of soils that were affected by wildfires that burned portions of the Everglades in the Spring of 2008. Soils at sites that were extensively burned exhibit a pronounced surface magnetic enhancement effect with magnetizations of surface samples up to 16 times greater than that observed at depth (>7 cm) at these sites. The increase in magnetization results from an increased abundance of a low-coercivity phase (maghemite) that occurs at the expense of the abundance of a high-coercivity phase (goethite). These results indicate that fire-induced heating caused goethite in the surface soils to convert into a more magnetic, low-coercivity phase, such as maghemite. Goethite is an excellent adsorber of phosphorus, and therefore we hypothesize that the destruction of goethite as a result of burning may have important implications for phosphorus cycling in the Everglades ecosystem. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: wildfire; magnetic enhancement; goethite; Everglades

Introduction

Soils often exhibit a magnetic surface enhancement effect in that the surface soils are much more magnetic than would be expected given the magnetic properties of the soil's parent material (Le Borgne, 1955, 1960; Mullins, 1977; Tite and Linington, 1975; Schwertmann and Taylor, 1977; Maher, 1986, 1998; Geiss *et al*., 2004; see Thompson and Oldfield, 1986; Evans and Heller, 1994, 2003, for summaries of literature in this area). The surface enhancement effect presents an apparent contradiction because weathering reactions generally lead to progressive oxidation of the residual minerals, which for most magnetic minerals converts them to a less magnetic phase (Mullins, 1977; Singer and Fine, 1989; Singer *et al*., 1996). In order for enhancement to occur, a process must take place that converts weakly magnetic iron oxides and oxy-hydroxides into more reduced, and more magnetic, mineral phases (Taylor and Schwertmann, 1974a, 1974b; Mullins, 1977; Rummery *et al*., 1979; Liu *et al*., 2003).

Wildfires are one mechanism that has been proposed to alter the magnetic properties of soils, leading to an enhancement of the surface magnetism (Le Borgne, 1955, 1960; Rummery *et al*., 1979; Schwertmann and Fechter, 1984; Kletetschka and Banerjee, 1995; Quirine *et al*., 2000; Blake *et al*., 2006; Oldfield and Crowher, 2007). Although the mechanisms by which fires might enhance the surface magnetization are not well documented, it has been proposed that high temperatures and changing oxidation/reduction conditions during fires act to convert less magnetic iron oxy-hydroxides into more highly magnetic phases such as maghemite. Heating iron oxy-hydroxides such as lepidocrocite or goethite in the presence of oxygen causes these minerals to convert into weakly magnetic phases such as hematite. However, when iron oxy-hydroxides are heated in the presence of organic matter (Oldfield *et al*., 1981; Hanesch *et al*., 2006) the reducing conditions that occur as the organic matter is burned may cause the iron oxy-hydroxides to convert to much more magnetic phases such as maghemite. Alternatively, Schwertmann and Fechter (1984) showed that heating aluminum substituted goethite (a common weathering product) produces aluminum substituted maghemite, a much more magnetic phase. They postulate that this is a common mechanism by which wildfires produce an enhancement of the surface magnetization.

A better understanding of the processes that affect the magnetic properties of surface soils may make it possible to use the mineral-magnetic record in soils to interpret the intensity and/or frequency of past fires that have affected an area. The Everglades provides a valuable natural laboratory to study the effects of wildfire on surface soils; natural fires occur frequently in the Everglades and play an important role in shaping this unusual ecosystem (Smith *et al*., 2001). We present here results of a rock-magnetic study of soils that were affected by fires that occurred in the Spring of 2008. This study was undertaken as part of a larger effort to monitor ecological variations in the marl prairies landscape in the southern

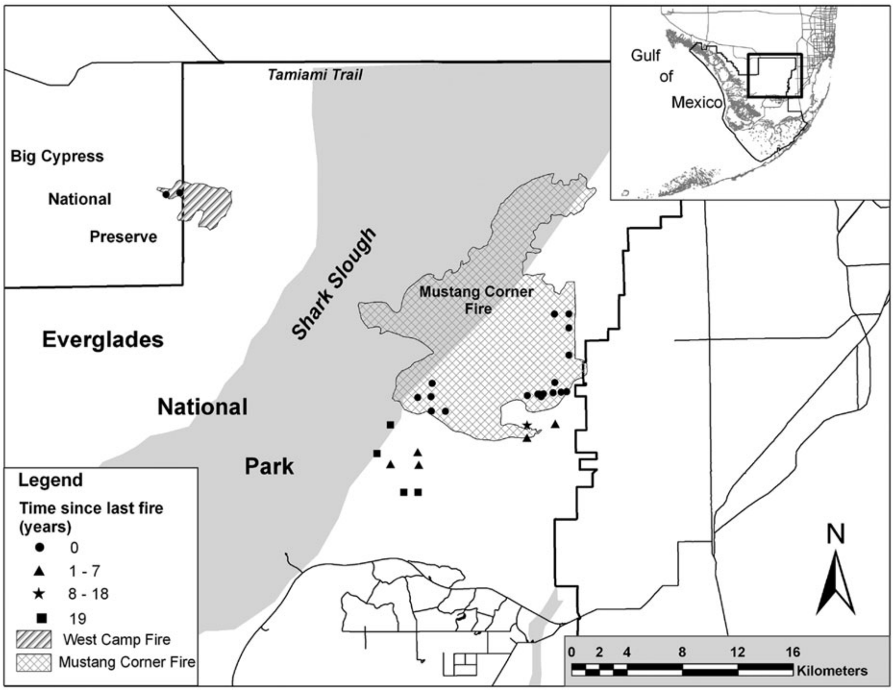

Figure 1. Map showing sampling locations and the areas of the Everglades burned in the West Camp and Mustang Corner fires during the Spring of 2008. The symbols showing the sampling locations are also keyed to indicate the fire history (the number of years since the most recent fire at that site).

Everglades, which is the only habitat of an endangered species, the Cape Sable seaside sparrow (Pimm *et al*., 2002; Ross *et al*., 2006). We were able to take advantage of the monitoring project to collect soil cores from well-characterized sites that had been affected by the fires. Our rock-magnetic results indicate that fire-induced heating caused goethite in the surface soils to convert into a more magnetic, low-coercivity phase, most likely maghemite. Because goethite is an excellent adsorber of phosphorus in aqueous environments (Patrick and Khalid, 1974; Parfitt and Atkinson, 1976; Torrent *et al*., 1990; van der Zee *et al*., 2003), the destruction of goethite during fires likely has important implications for phosphorus cycling in the Everglades ecosystem.

Methods

The soils in our sampling area are shallow, usually consisting of only 10 to 15 cm of freshwater marl overlying the limestone bedrock (Nobel *et al*., 1996; Corstanje *et al*., 2006). Bedrock in the Everglades consists of a highly porous limestone, and the overlying soils contain a large percentage of biogenically precipitated freshwater carbonate with smaller amounts of clays. In this aspect these soils are very different from a more typical soil that is formed as the weathering residue from the bedrock. These soils are located in southern Everglades marl prairies that are seasonally inundated by water, being submerged for an average of three to six months every year. The seasonal drying cycle results in precipitation of iron oxy-hydroxides from the ground/surface water onto surface materials as they dry (Zhou and Li, 2001). This is the same well-recognized process that causes significant yellow-brown staining of buildings and structures in the south Florida region as irrigation waters dry on surfaces leaving an iron oxy-hydroxide precipitate.

In the Spring of 2008 two large wildfires burned portions of the southern Everglades. The Mustang Corner fire burned 15,971 ha (39,465 acres), between May 14 to June 14, 2008. The West Camp fire started on June 22, 2008 and burned 997 ha (2465 acres) (Figure 1). These fires affected vegetation survey sites in the southern Everglades, which are being studied as part of an ongoing project to monitor ecological conditions within the habitat of the Cape Sable seaside sparrow. At each of these sites vegetation data, hydrologic data, organic carbon content, iron concentration and the fire history (burn frequency and time since the most recent burn) are available.

We collected 20 soil cores (10–13 cm long) from within the fire boundaries, and 10 cores from nearby unburned sites (Figure 1). The cores were collected in marl prairies where the major vegetation is sawgrass (*Cladium jamaicense*). The sampling sites are located in areas of generally uniform vegetation, however, small scale variations in topography due to micro-karst features and the varying amounts of vegetative cover likely resulted in significantly different amounts of fuel for the fires at each site. This small-scale variability in fuel load suggests that the intensity of the fires likely varied on a similar scale. Therefore the distances separating our sampling localities likely far exceed the typical spatial scale of fire intensity.

Because these were wildfires, no independent, direct measures of the intensity of the fires were available. Therefore, at each site we estimated the local intensity of the fire based on the percentage of the surface area that was visibly burned in 60 m × 1 m belt transects that are used as vegetation survey tracts. We collected soil cores from within these survey tracts. Previous studies suggest that only the upper few centimeters of soils are heated by surface fires (Monson *et al*., 1974; Iverson and Hutchinson, 2002; Raison *et al*., 1986). For this reason, we sub-sampled each core by taking samples from the surface, from the 2 cm depth interval and from close to the base of each core (between 7 cm to 13 cm depth).

Because most of the sites are only accessible by helicopter, we were unable to occupy the sites immediately following the fires, and had to wait until a scheduled survey in July. As a result the wet season had begun before we were able to collect the cores. Therefore it was not possible to determine how wet the soils in the sampled areas were during the fire. Nor was it possible to determine the local hydrologic history since the fire.

The samples were subjected to a suite of rock-magnetic measurements designed to identify the major magnetic miner-

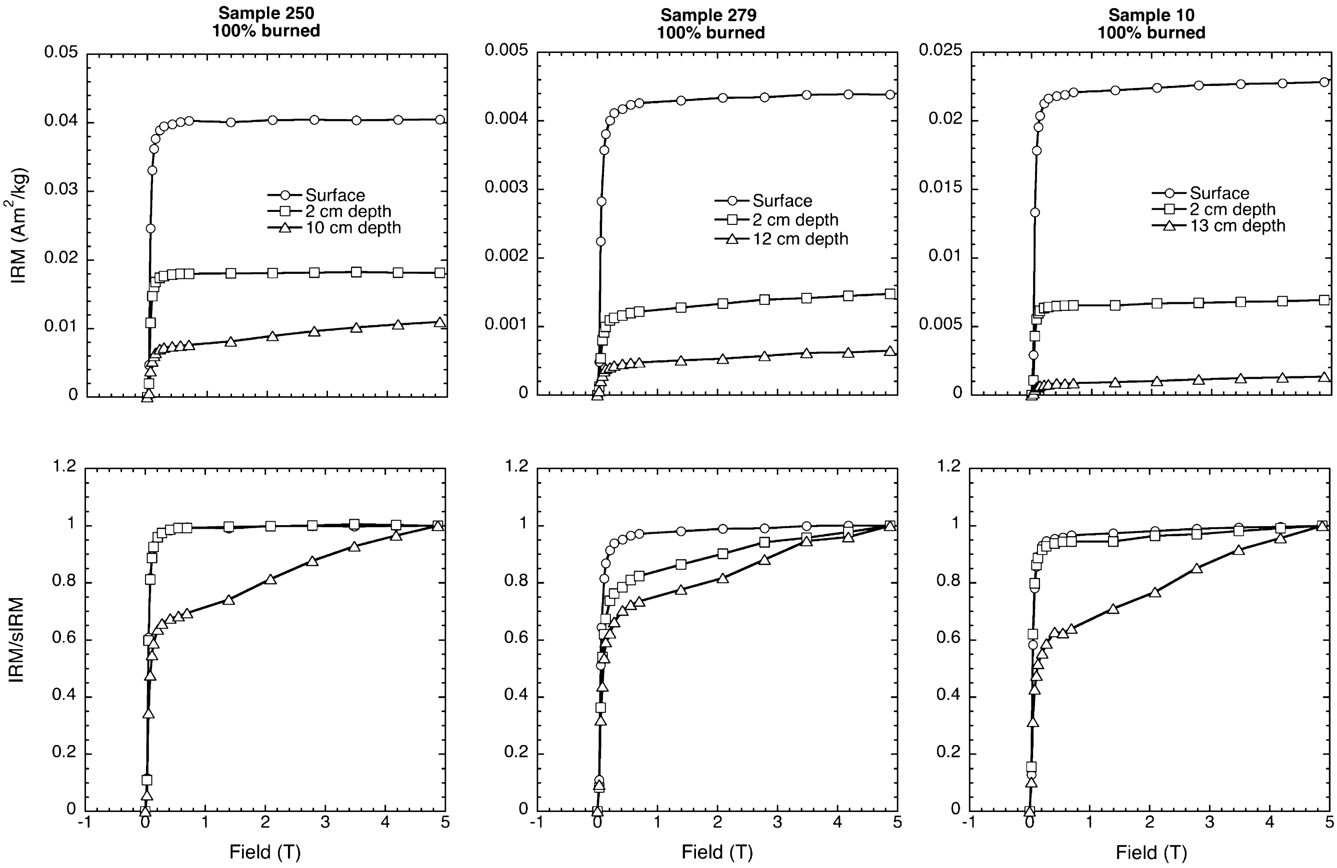

Figure 2. IRM acquisition curves from cores collected at sites that were completely burned. Total IRM values are shown in the top panel, normalized values for the same samples are shown in the lower panel. These samples show a dramatic enhancement of magnetization in shallow and surface soils. The lower panels demonstrate that the enhancement results from a change in the type of magnetic material present, not simply an increase in the concentration of magnetic carriers in the surface samples.

als present in these soils and to constrain their relative concentrations. These measurements include initial susceptibility and frequency-dependent susceptibility made using a Bartington susceptibility meter, anhysteretic remanent magnetization acquisition and isothermal remanent magnetization (IRM) acquisition, made using a Molspin AF demagnetizer and an ASC impulse magnetizer with a coil allowing generation of impulse fields of up to 5 T. The remanences were measured on a 2G superconducting rock magnetometer equipped with DC squid sensors.

Results

Of the different rock magnetic experiments conducted, IRM acquisition curves proved to be the most useful because of the importance of very high-coercivity components (observed at fields > 3 T) that could not be detected using other types of measurements. Low field susceptibility measurements and hysteresis measurements (that only went up to 1·5 T), yielded less systematic results largely because these measurements are relatively insensitive to the high coercivity carriers that the IRM experiments show are present. In addition, the IRM acquisition experiments demonstrate that most samples contain mixtures of magnetic remanence carriers, which are more straightforward to interpret in IRM acquisition experiments (Kruiver *et al.*, 2001; France and Oldfield, 2000) than other measurements. It is important to note that the occurrence of goethite in these samples would have gone largely unrecognized were it not for the high-field, impulse magnetizer used in this study.

Cores collected from sites characterized as having been 100% burned during the 2008 fires exhibit a large surface magnetic enhancement effect (Figure 2). Samples from the soil surface exhibit saturation IRMs that are many times (from 1·5 to 16 times) more magnetic than observed at depth in the same cores. The intensity of the magnetization varies systematically with depth in these cores. Samples from the 2 cm depth are consistently less magnetic than the surface samples, and samples from the deepest portions of the cores are even less magnetic.

The increase in saturation isothermal remanent magnetizations (sIRM) in the surface samples does not result solely from an increase in the concentration of the magnetic carrier. Instead, the composition of the magnetic carrier also varies systematically with depth (Figure 2). Deeper samples contain a progressively greater percentage of a high-coercivity carrier. In these deeper samples, the IRMs do not saturate even in impulse fields approaching 5 T, suggesting that the remanence is carried by goethite (Dunlop and Ozdemir, 1997).

Cores collected from nearby sites that were not affected by the fires exhibit very different behavior. In these cores samples from both surface and sub-surface are characterized by high-coercivity magnetizations (Figure 3). Although the surface samples are still more magnetic than those at depth in the majority of these cores, the variation with depth is less systematic. The extent of this variation likely results from variations in the burn histories of the sites, variations in the hydrology at the sites as well as variations in the soil composition.

In order to determine if the high-coercivity magnetization observed in these samples is carried by goethite or hematite,

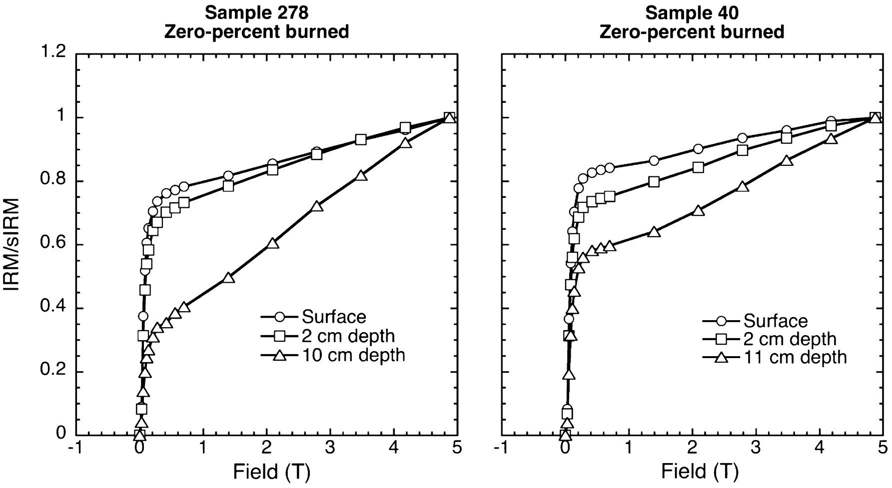

Figure 3. Normalized IRM acquisition curves for samples collected at sites that had not been burned. Even in the surface soils, 20% or more of the total remanence is carried by high-coercivity carriers. Because the saturation magnetization of common high-coercivity minerals is two-orders of magnitude less than the saturation magnetization of magnetite or maghemite, the magnetizations indicate a much greater abundance of the high-coercivity minerals than low-coercivity minerals in these samples.

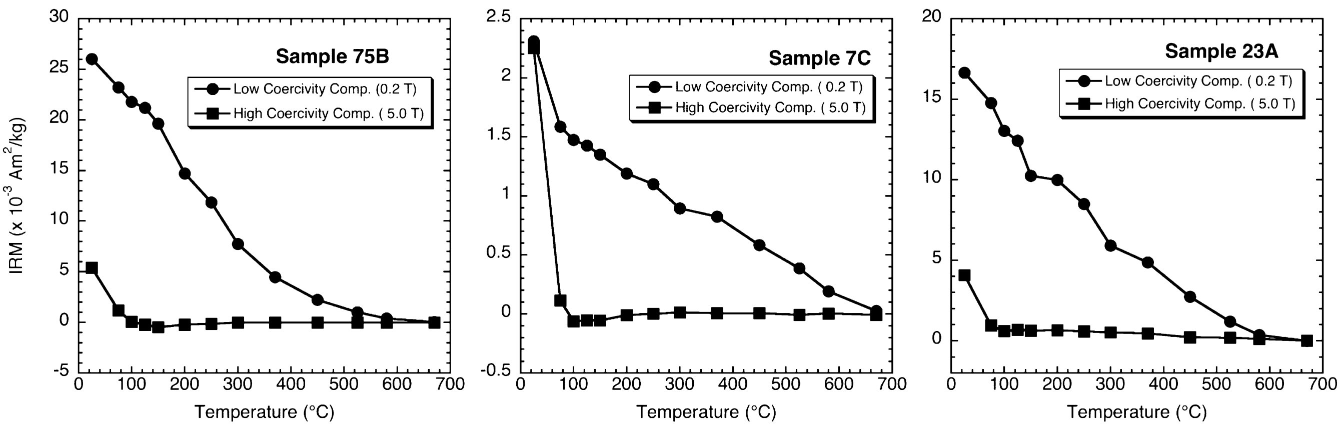

Figure 4. Progressive thermal demagnetization of orthogonal two-component IRMs. Filled squares represent demagnetization of the component acquired by exposure to a 5 T field. Filled circles represent demagnetization of a component acquired by exposure to a 0·2 T field. The high-coercivity component is completely demagnetized by treatment at temperatures of 100 °C to 125 °C indicating that this component is carried exclusively by goethite.

we conducted progressive thermal demagnetization of orthogonal two-component IRMs (imparted at 5 T along the *Z*-axis of the sample and 0·2 T along the *X*-axis of the sample) (Lowrie, 1990; France and Oldfield, 2000). Results of these experiments show that the highest coercivity component is completely unblocked at temperatures of 100 °C to 125 °C, consistent with the maximum unblocking temperatures of goethite (Figure 4). In most samples the low coercivity magnetizations are completely unblocked at temperatures ranging from 500 °C to 580 °C. Changes in the slope of the thermal demagnetization curves suggests that the original low-coercivity carrier may be maghemite that alters to magnetite during demagnetization (possibly because of the presence of aluminum-substituted maghemites in the unheated samples). In one sample, the low-coercivity IRM is not unblocked until treatment at 670 °C, indicating a hematite remanence. The hematite must be formed during thermal demagnetization because there is no indication of it in the initial high-field IRM component. It is probable that maghemite in this sample was converted to hematite above temperatures of 350 °C. The offset in the trajectory of the demagnetization plot at 350 °C suggests this may indeed be the case. Extrapolation of the slope (before treatment at 350 °C) leads to a zero magnetization at approximately 580 °C. However at treatments above 350 °C the trend is systematically offset toward higher temperatures, being completely demagnetized at 670 °C.

Comparison of IRM acquisition curves imparted before and after thermal demagnetization shows that the high-coercivity carrier (goethite) is destroyed during heating and replaced by a low-coercivity carrier with a resulting sIRM that is more than 10 times greater that the pre-heating sIRM (Figure 5). The lower coercivity component observed after heating exhibits a distributed range of coercivities; it does not saturate until treatment at 0·6 to 0·8 T. This indicates that an oxidized maghemite rather than magnetite was likely the magnetic phase created during heating.

Discussion

At burned sites in our study, surface soils show a significant increase in remanent magnetizations relative to the magnetizations observed at depth at those sites. The increased magnetizations observed in the shallow samples appear to result from an increasingly dominant low-coercivity component. The low-coercivity component exhibits both an increase in absolute intensity as well as an increase in the percentage of the total remanence in surface samples as compared with samples at depth. Unmixing the IRM acquisition curves using the techniques described by Kruiver *et al.* (2001), indicates that the acquisition curves from all samples may be well-fit using two magnetization components. The first component consistently has coercivities, B_{cr}', of 40–60 mT (consistent with maghemite) and the second component has B_{cr}' values of 3100–3900 mT (consistent with goethite) (Dekkers, 1989, 1990; France and Oldfield, 2000; Maher *et al.*, 2004). Unmixing the acquisition

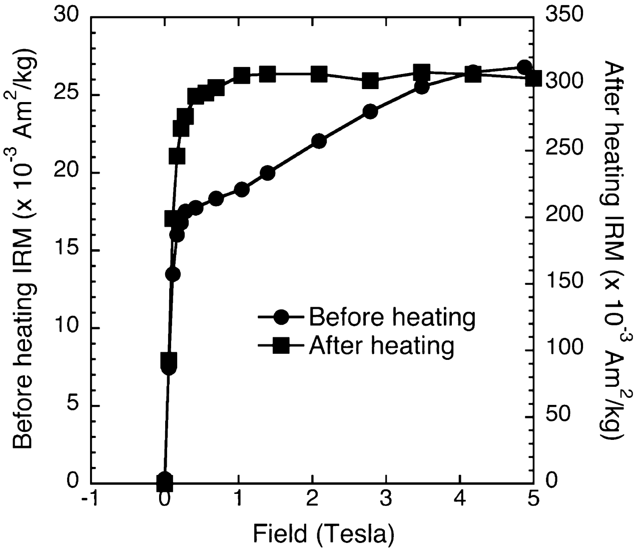

Figure 5. IRM acquisition curves obtained before and after the sample was heated. Filled circles represent the IRM acquisition curve measured before the sample was subjected to progressive thermal demagnetization. The pre-heating IRM curve exhibits a major contribution from very high-coercivity mineral(s) (saturation is not reached by 5 T). After heating, the IRM acquisition curve shows that the high-coercivity component is absent and that the IRM is dominated by a much lower coercivity carrier. The resulting sIRM is more an order of magnitude greater than the sIRM observed prior to heating. These results demonstrate that heating the soils under laboratory conditions destroys goethite present in these soils, replacing it with maghemite.

curves shows that at burned sites, the increase in the total sIRM observed in surface samples occurs as a result of both an increase in the magnetization of the low-coercivity component as well as a decrease in the high-coercivity component (in many cases to zero), as compared with the magnetizations observed at depth. Therefore the dominance of the low-coercivity component in burned surface samples is not due just to the addition of low-coercivity material, but also results from the removal of the high-coercivity component.

These results indicate that the fires have caused goethite in these soils to convert into a more magnetic phase, most probably maghemite. This conversion is clearly seen at sites that were completely burned and appears not to have occurred at sites that were not affected by these fires. A range of magnetic behavior is observed at sites where the intensity of the fire was estimated to fall somewhere in between these two extremes. The extent to which the surface samples exhibit complete saturation in the IRM curves, may provide insights into the extent to which these samples have been heated. For example, the results from the surface samples shown in Figure 2, clearly show a dramatic increase in the percentage of the remanence carried by a low coercivity carrier(s) relative to deeper samples, however these samples still exhibit a range in degree of saturation. In this case, we would hypothesize that sample 250 had been heated to higher temperatures than either samples 279 or 10, because sample 250 is completely saturated whereas the other two samples still contain very small contributions from high-coercivity components. If we assume that the samples at depth in each core are representative of the surface samples in that core prior to being affected by fire, then the variation with depth may provide an important indicator of just how severely the surface samples were heated and the depth to which elevated temperatures were experienced. We hypothesize that mineral-magnetic profiles of soils in this area may provide a method for determining the intensity of fires and may provide a way to characterize the burn history of a site in the Everglades.

A major uncertainty in this study is the lack of independent, quantitative measures of the maximum temperatures the soils experience during these fires, and the depth within the soils to which those elevated temperatures extended. The intensity of a fire depends upon a number of factors, including the fuel load, the vegetation cover in the area, and the recent hydrologic history of the site. Future studies using controlled micro-burns with thermocouples deployed with depth are required to calibrate the changes in magnetic properties directly with temperature.

Another uncertainty affecting the interpretation of our results is the variability of the local hydrological history at these sites. We were not able to sample these sites immediately following the fires, but had to wait until the wet season was well underway. As a result, some sites had experienced considerable rainfall since the fire, and the rain events may have affected the distribution of fine particles with depth. This would have the effect of overestimating the depth to which significant heating had occurred. Fires usually produce steep temperature gradients in soils with only the upper few centimeters elevated to high temperatures. The temperature gradient has been related to fuel load and soil moisture content amongst other variables (Monson *et al.*, 1974; Iverson and Hutchinson, 2002; Raison *et al.*, 1986). The observation of conversion of goethite to maghemite at depth might be a result of very intense heating or alternatively, it could result from downward transport of fine-grained minerals by rains that fell after the fires but prior to our sampling.

Possible effects on phosphorus cycling

Iron oxy-hydroxides, especially goethite, are known to be important adsorbers of phosphorus in aquatic systems (Parfitt and Atkinson 1976; van der Zee *et al.*, 2003; Chambers and Odum, 1990; Torrent *et al.*, 1990; Patrick and Khalid, 1974). Our thermal demagnetization experiments confirm that the high-coercivity carrier in the sediments we sampled is goethite. Determining the absolute concentrations of goethite in these soils is difficult to do based on magnetic measurements because of the sensitivity of the magnetic properties to the extent of crystallinity and impurities in the goethite. Previous studies of the mineralogy of the surface soils in the Everglades indicate relatively high concentrations (Zhou and Li, 2001) that are consistent with our observations. The occurrence of goethite in these soils is particularly important because phosphorus is a limiting nutrient in the Everglades prairies and marshes (Zhou and Li, 2001). Zhou and Li (2001) have shown that the non-carbonate clays (including iron-oxides and iron-oxyhydroxides) in calcareous soils from south Florida have a strong affinity for phosphorus.

The results presented here demonstrate that heating surface soils during wildfire converts goethite to low-coercivity phases such as maghemite. We hypothesize that the destruction of goethite will release the phosphorus that had been adsorbed onto it (Patrick and Khalid, 1974; Parfitt and Atkinson, 1976; Torrent *et al.*, 1990; van der Zee *et al.*, 2003). Therefore these results may have important implications for the role of fires in the phosphorus cycle. The extent of goethite destruction and therefore the amount of phosphorus released likely depends on the thickness of the surface soil that is heated to high enough temperatures to cause the dehydration of goethite. This in turn depends upon the intensity of the fire. Future work studying controlled burns where we can measure the temperature profile with depth and measure phosphorus contents of soil cores before and after heating is required to determine quantitatively the importance of this process to the overall phosphorus cycle in the Everglades.

Acknowledgments—This work was supported by an REU grant from the Florida Coastal Everglades LTER that was funded by the US National Science Foundation. We thank the Everglades National Park for allowing samples to be collected within the park. We also thank two anonymous reviewers for comments that significantly improved the manuscript.

References

Blake WH, Wallbrink PJ, Doerr SH, Shakesby RA, Humphreys GS. 2006. Magnetic enhancement in wild-fire affected soil and its potential for sediment-source ascription. *Earth Surface Processes and Landforms* **31**: 249–264. DOI. 10.1002/esp.1247

Chambers RM, Odum WE. 1990. Porewater oxidation, dissolved phosphate and the iron curtain. *Biogeochemistry* **10**: 37–52. DOI. 10.1007/BF00000891

Corstanje R, Grunwald S, Reddy KR, Osborne TZ, Newman S. 2006. Assessment of the spatial distribution of soil properties in a northern Everglades marsh. *Journal of Environmental Quality* **35**: 938–949. DOI. 10.2134/jeq2005.0255

Dekkers MJ. 1989. Magnetic properties of natural goethite, I. Grain-size dependence of some low- and high-field related rock magnetic parameters measured at room temperature. *Geophysical Journal International* **97**: 323–340. DOI. 10.1111/j.1365-246X.1989.tb00504.x

Dekkers MJ. 1990. Magnetic properties of natural goethite, III. Magnetic behaviour and properties of minerals originating from goethite dehydration during thermal demagnetization. *Geophysical Journal International* **103**: 233–250. DOI. 10.1111/j.1365-246X.1990.tb01765.x

Dunlop DJ, Ozdemir O. 1997. Rock magnetism: fundamentals and frontiers. In *Cambridge Studies in Magnetism*, Edwards D (ed.) Cambridge University Press: Cambridge; 573.

Evans ME, Heller F. 1994. Magnetic enhancement and palaeoclimate: study of a loess/palaeosol couplet across the Loess Plateau of China. *Geophysical Journal International* **117**: 257–264. DOI. 10.1111/j.1365-246X.1994.tb03316.x

Evans ME, Heller F. 2003. *Environmental Magnetism*. Elsevier: New York; 299 pp.

France DE, Oldfield F. 2000. Identifying goethite and hematite from rock magnetic measurements of soils and sediments. *Journal of Geophysical Research* **105**: 2781–2795. DOI. 10.1029/1999JB900304

Geiss CE, Zanner CW, Banerjee SK, Joanna M. 2004. Signature of magnetic enhancement in a loessic soil in Nebraska, United States of America. *Earth and Planetary Science Letters* **228**: 355–367. DOI. 10.1016/j.epsl.2004.10.011

Hanesch M, Stanjek H, Petersen N. 2006. Thermomagnetic measurements of soil iron minerals; the role of organic carbon. *Geophysical Journal International* **165**: 53–61. DOI. 10.1111/j.1365-246X.2006.02933.x

Iverson LR, Hutchinson TF. 2002. Soil temperature and moisture fluctuations during and after prescribed fire in mixed-oak forests, USA. *Natural Areas Journal* **22**: 296–304.

Kletetschka G, Banerjee SK. 1995. Magnetic stratigraphy of Chinese loess as a record of natural fires. *Geophysical Research Letters* **22**: 1341–1343. DOI. 10.1029/95GL01324

Kruiver PP, Dekkers MJ, Heslop D. 2001. Quantification of magnetic coercivity components by the analysis of acquistion curves of isothermal remanent magnetization. *Earth and Planetary Science Letters* **189**: 269–276. DOI. 10.1016/S0012-821X(01)00367-3

Le Borgne E. 1955. Abnormal magnetic susceptibility of the top soil. *Annals of Geophysics* **11**: 399–419.

Le Borgne E. 1960. Influence du feu sur les properties magnetiques du sol et du granite. *Annals of Geophysics* **16**: 159–195.

Liu QS, Banerjee SK, Jackson MJ, Chen F, Pan Y, Zhu R. 2003. An integrated study of the grain-size-dependent magnetic mineralogy of the Chinese loess/paleosol and its environmental significance. *Journal of Geophysical Research* **108**: 2437. DOI. 10.1029/2002JB002264

Lowrie W. 1990. Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. *Geophysical Research Letters* **17**: 159–162. DOI. 10.1029/GL017i002p00159

Maher BA. 1986. Characterization of soil by mineral magnetic measurements. *Physics of the Earth and Planetary Interiors* **42**: 76–92. DOI. 10.1016/S0031-9201(86)80010-3

Maher BA. 1998. Magnetic properties of modern soils and Quaternary loessic paleosols: paleoclimatic implications. *Paleogeography, Paleoclimatology and Paleoecology* **137**: 25–54. DOI. 10.1016/S0031-0182(97)00103-X

Maher BA, Karloukovski VV, Mutch TJ. 2004. High-field remanence properties of synthetic and natural submicrometre haematites and goethites: significance for environmental contexts. *Earth and Planetary Science Letters* **226**: 491–505. DOI. 10.1016/j.epsl.2004.05.042

Monson WG, Burton GW, Williams EJ, Butler JL. 1974. Effects of burning on soil temperature and yield of coastal bermudagrass. *Agronomy Journal* **66**: 212–214.

Mullins CE. 1977. Magnetic susceptibility of the soil and its significance in soil science: a review. *Journal of Soil Science* **28**: 223–246. DOI. 10.1111/j.1365-2389.1977.tb02232.x

Nobel CV, Drew RRW, Slabaugh JD. 1996. *Soil Survey of Dade County Area, Florida*, US Department of Agriculture, NRCS Report. US Department of Agriculture: Washington, DC; 116.

Oldfield F, Crowher J. 2007. Establishing fire incidence in temperate soils using magnetic measurements. *Paleogeography, Palaeoclimatology and Palaeoecology* **249**: 362–369. DOI. 10.1016/j.palaeo.2007.02.007

Oldfield F, Thompson R, Dickson DPE. Artificial magnetic enhancement of stream bedload: a hydrological application of superparamagnetism. *Physics of the Earth and Planetary Interiors* **26**: 107–124.

Parfitt RL, Atkinson RJ. 1976. Phosphate adsorption on goethite (a-FeOOOH). *Nature* **264**: 740–742. DOI. 10.1038/264740a0

Patrick Jr WH, Khalid RA. 1974. Phosphate release and sorption by soils and sediments: effect of aerobic and anaerobic conditions. *Science* **186**: 53–55. DOI. 10.1126/science.186.4158.53

Pimm SL, Lockwood JL, Jenkins CN, Curnutt JL, Nott P, Powell RD, Bass Jr OL. 2002. *Sparrow in the Grass: A Report on the First Ten Years of Research on the Cape Sable Seaside Sparrow (*Ammodramus maritimus mirabilis*)*. Everglades National Park: Homestead, FL.

Quirine M, Ketteringsa JM, Bighamb M, Lapercheb V. 2000. Changes in soil mineralogy and texture caused by slash-and-burn fires in Sumatra, Indonesia. *Soil Science Society of America Journal* **64**: 1108–1117.

Raison RJ, Woods PV, Jakobsen BF, Bary GAV. 1986. Soil temperatures during and following low-intensity prescribed burning in a Eucalyptus pauciflora forest. *Australian Journal of Soil Research* **24**: 33–47. DOI. 10.1071/SR9860033

Ross MS, Sah JP, Snyder JR, Ruiz PL, Jones DT, Cooley HC, Travieso R, Hagayari D. 2006. *Effect of Hydrology Restoration on the Habitat of the Cape Sable Seaside Sparrow*, Annual Report of 2004–2005. Everglades National Park: Homestead, FL.

Rummery TA, Bloemendal J, Dearing J, Oldfield F. 1979. The persistence of fire-induced magnetic oxides in soils and lake sediments. *Annales de Geophysique* **35**: 103–107.

Schwertmann U, Fechter H. 1984. The influence of aluminum on iron oxides: XI. Aluminum-substituted maghemite in soils and its formation. *Soil Science Society of America Journal* **48**: 1462–1463.

Schwertmann, Taylor RM. Iron oxides. In: JB Dixon and SB Weed, Editors, *Minerals in Soil Environments*, Soil Sci. Soc. Am, Madison, Wisc (1977), 145–180.

Singer MJ, Fine P. 1989. Pedogenic factors affecting magnetic susceptibility of northern California soils. *Soil Science Society of America Journal* **53**: 1119–1127.

Singer MJ, Verosub KL, Fine P, TenPas J. 1996. A conceptual model for the enhancement of magnetic susceptibility in soils. *Quaternary International* **34**: 243–248. DOI. 10.1016/1040-6182(95)00089-5

Smith SM, Newman S, Garrett PB, Leeds JA. 2001. Differential effects of surface and peat fire on soil constituents in a degraded wetland of the northern Florida Everglades. *Journal of Environmental Quality* **30**: 1998–2005. PMid:11790006

Taylor RM, Schwertmann U. 1974a. Maghemite in soils and its origin. I. *Clay Minerals* **10**: 289–298. DOI. 10.1180/claymin.1974.010.4.07

Taylor RM, Schwertmann U. 1974b. Maghemite in soils and its origin. II. Maghemite synthesis at ambient temperature and pH 7. *Clay Minerals* **10**: 299–310. DOI. 10.1180/claymin.1974.010.4.08

Thompson R, Oldfield F. 1986. *Environmental Magnetism*. Allen and Unwin: London; 227 pp.

Tite MS, Linington RE. 1975. Effect of climate on the magnetic susceptibility of soils. *Nature* **256**: 565–566. DOI. 10.1038/256565a0

Torrent JV, Barron V, Schwertmann U. 1990. Phosphate adsorption and desorption by goethites differing in crystal morphology. *Soil Science Society of America Journal* **54**: 1007–1012.

Van der Zee C, Roberts DR, Rancourt DG, Slomp CP. 2003. Nanogoethite is the dominant reactive oxyhydroxide phase in lake and marine sediments. *Geology* **31**: 931–996. DOI. 10.1130/G19924.1

Zhou M, Li YC. 2001. Phosphorus-sorption characteristics of calcareous soils and limestone from the southern Everglades and adjacent farmlands. *Soil Science of America Journal* **65**: 1404–1412.