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Sensor mapping of Amazonian Dark Earths in deforested croplands

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ABSTRACT

Amazonian Dark Earths (ADEs) are fertile soils for agricultural production as well as important archaeological resources for understanding the pre-Columbian past of the Neotropical lowland rainforest. ADEs are threatened by expanding land exploitation and there is a need to develop efficient approaches to soil mapping and analysis for documenting these soils. In this paper we assess the potential of satellite remote sensing and proximal soil sensing to map, predict and monitor ADEs in land affected by agro-industrial development. We use instruments based on portable x-ray fluorescence (PXRF) and electromagnetic induction (EMI) as well as high-resolution satellite data (Spot 6) for detailed soil surveys at a 10-ha ADE site now mainly used for soybean production on the Belterra Plateau, Pará, Brazil. We predict the regional occurrence of ADE in a c. 250 km^2 test area centred on the known ADE site São Francisco using satellite data. Multivariate adaptive regression splines models were parameterised for predictions of soil organic carbon (SOC), cation exchange capacity (CEC), phosphorus (P) and depth of the A horizon in ADEs from sensor data – both from individual sensors and in sensor combinations. Combining sensors gave the best validation results: the highest modelling efficiencies (E) were 0.70 (SOC), 0.88 (CEC) and 0.74 (for both P and A depth). The most powerful single proximal sensor outputs in the predictions were Sr from the PXRF data and magnetic susceptibility (MSa) as measured by the EMI instrument. In the regional satellite based model we located 17 previously unrecorded ADE sites >2 ha. Ground control checks showed that 10 out of 11 sites were correctly classified. We conclude that these sensors are useful in studies of ADE in deforested cropland and provide new opportunities for detailed studies of the archaeological record.

1. Introduction

Amazonian Dark Earths (ADEs; also known as *terras pretas*) rich in nutrients, organic matter and carbon in the very stable form of biochar (pyrogenic carbon) are unique agricultural resources distinct from the strongly weathered soils that dominate in the Amazon. ADEs are of great interest as providers of important ecosystem services and as multi-facetted and rich archaeological sources of information that have helped to revise the interpretation of pre-Columbian Amazonia. ADEs contain high frequencies and densities of cultural artefacts, and archaeological and pedological investigations demonstrate that ADEs have formed as a result of human activities mainly during the later pre-Columbian period (c. CE 0–1500) (Glaser and Birk, 2012; Steiner et al., 2004; Woods and Denevan, 2010). Owing to their capacity to sequester carbon and hold soil nutrients ADEs form important models for current efforts to produce soils with similar qualities, particularly in the tropics (Lehmann, 2007; Lehmann and Joseph, 2009; Verheijen et al., 2010). In Amazonia, ADE patches vary in size from under a hectare to several hundred hectares and are highly valued by farmers, both smallholders and large-scale soybean producers. Incited by regional and national economic growth interests and the demand for protein fodder in the global livestock industry, ADEs have increasingly been brought under agro-industrial cultivation (Morton et al., 2006; Richards et al., 2015). The expansion of agro-industrial production has propelled intense debates over environmental and social impacts and load displacements (e.g. Hornborg, 2009). As part of this critique it has largely been assumed rather than shown in detail that agro-industrial land management erodes the long-term conservation of both the agricultural and archaeological properties of ADEs. In the Santarém-Belterra

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region of the Brazilian Amazon in western Pará, deforestation associated with cash-crop mono-cropping for national and global fodder markets and cattle breeding for meat production has precipitated fundamental landscape change over the last decades (Fig. 1) (Corrêa et al., 2011); the inauguration of a modern grain terminal for oceanic transportation at the port of Santarém in 2003 facilitated this development. Based on current understanding of the distribution of ADE sites in this region (Nimuendajú, 2004; Söderström et al., 2013; Stenborg et al., 2012) we know that land clearance often will, intentionally or unintentionally, make ADEs available to agro-industrial farming. In the face of the ongoing exploitation of land in the region it is of fundamental concern to develop methods for mapping, predicting and assessing how large-scale cultivation using modern methods affect the archaeological and pedological record, as well as to monitor its effects on soil quality.

Despite an increasing volume of inter-disciplinary ADE research over the last two decades regional and local-scale mapping of ADE is fragmentary and remains largely in its infancy. Current distribution maps indicate clustering on floodplain bluffs of major rivers and near current population centres, such as at the soybean frontier in the Santarém-Belterra area (McMichael et al., 2014), but there may be a bias towards accessible areas (WinklerPrins and Aldrich, 2010). Hence, there is a need to develop efficient approaches to soil mapping and analysis for documenting ADEs. In recent years, digital soil mapping (DSM) has been developed as a cost-efficient approach to predict spatial patterns of soil properties across geographical scales by integrating quantitative methods with proximal and remote sensing imagery, soil data and other covariates such as digital elevation data (Boettinger, 2010; Minasny et al., 2008). DSM is particularly useful in regions, such as the Amazon, where the available information on the quality of land and soil resources that guides land-use planning is often fragmentary and coarse in resolution; in the Amazon region only very general soil maps are available except in smaller areas where more detailed surveys have been carried out (Fearnside and Leal Filho, 2001; Quesada et al., 2011; Teixeira et al., 2008).

Thayn et al. (2011) discuss the possibility to use satellite based remote sensing for locating ADE in forested parts of the Amazon Basin, in particular by correlating differences in vegetation composition with soil quality, thus distinguishing forest on ADE soils from forest on the relatively poor soils that dominate the region. Another far more straightforward approach is to use satellite-based remote sensing in areas with limited vegetation, such as those cleared for mechanized agriculture. Mostly applied in local-scale studies, proximal soil sensing (PSS; when sensors are used in close contact with or within a distance of a few meters from the soil) is a way to rapidly and often non-

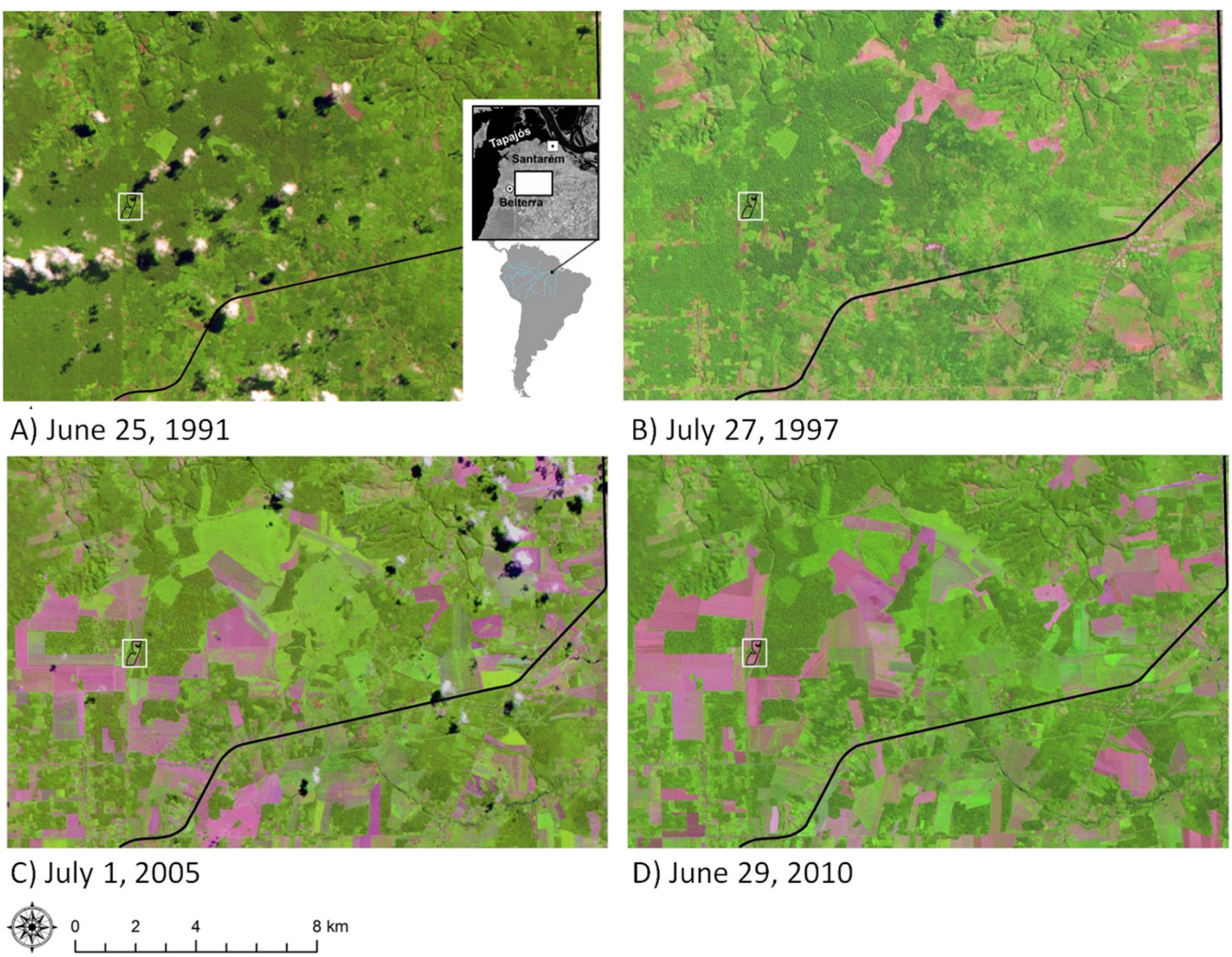

Fig. 1. A–D. Land-use change in the Amazon near the confluence of the Tapajós and Amazon Rivers (see inset in A). Over this 19 year period the character of land use changes from small-scale, forest-fallow smallholder agriculture and forest to large fields of mechanized agriculture dominated by soybean production. Landsat 5 images 1991–2010 of the Belterra Plateau study area south of Santarém city in Pará, Brazil. Colour and structure can be used for interpretation, e.g.: dark green = forest; large, homogenous light green areas = agricultural land with vegetation; violet = agricultural fields without vegetation. The black line represents road BR-163. The white square shows the location of Fig. 2.