Research Application Summary

Mineralogy of Africa's soils as a predictor of soil fertility

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Abstract

Soil mineralogy is essential to understanding many facets of land use and a key determinant of all soil functional properties that are expensive or time-consuming to measure, and can solve specific agricultural and environmental problems. They provide physical support for plants, contribute to soil structural formation, are sources of many soil nutrients, and can act as sorbents of several environmental pollutants. Soil mineralogy in Africa has not been adequately and appropriately researched upon. Poorly and fragmentally coordinated scientific investigations coupled with the limitations in the traditional analysis techniques are partly responsible for the limited studies so far executed. Land Degradation Surveillance Framework is a methodology designed for understanding ecological variables/metrics and their dynamics at different spatial scales. The aim of this study was to evaluate the ability of X-ray diffraction (XRD) techniques to rapidly predict soil functional properties and to develop pedo-transfer functions for Africa's soils. Geo-referenced samples associated with the Africa Soil Information Service (AfSIS), taken from a set of sentinel sites randomised over sub-Saharan Africa were used for characterisation. A total of 160 topsoil samples taken from 16 randomised points of ten 100-km^2 sites: Tanzania (3 sites), Malawi (2 sites), Mali (1 site), Burkina Faso (1 site), Kenya (2 sites) and Ghana (1 site) were characterised for chemical properties, particle sizes distribution, engineering properties and bulk mineralogy. Variation of the mineralogy within and between sites was explored using multivariate analysis, including principal component analysis in R statistical software, as a precursor to exploring relationships with directly measured soil properties and soil fertility diagnostics. The clustering of individual minerals and the distributions of the soil fertility variables identified across the sites appeared to relate to differences in mineralogical functional groups, supporting the understanding of the pedologic environment differences and similarities. The findings therefore present opportunity to improve soil assessment using information on soil mineralogy. For instance XRD information on mineralogy can be combined with information from infrared spectroscopy, which characterises soil mineral and physio-chemical properties, to provide powerful diagnostic capabilities, and be used as a complementary input to pedo-transfer functions for low cost and rapid prediction of soil functional properties.

Key words: Africa's soils, diagnostic surveillance, infrared spectroscopy, multivariate analysis, pedo-transfer functions, soil fertility, soil mineralogy, spectral diagnostics , X-ray diffraction

Résumé

La minéralogie des sols est essentielle pour comprendre de nombreux aspects de l'utilisation des terres et un déterminant clé de toutes les propriétés fonctionnelles du sol qui sont coûteuses ou chronophages pour mesurer, et peut résoudre des problèmes spécifiques de l'agriculture et de l'environnement. Elles apportent un soutien physique pour les plantes, contribuent à la formation structurale du sol, sont des sources de nombreux éléments nutritifs du sol, et peuvent agir en tant que absorbants de plusieurs polluants de l'environnement. La minéralogie des sols en Afrique n'a pas été d'une manière adéquate et appropriée l'objet de recherche. Les enquêtes scientifiques mal coordonnées et éparpillées, couplées aux limitations dans les techniques d'analyse traditionnelles sont responsables des études limitées jusqu'à présent exécutées. Le cadre de surveillance de la dégradation des terres est une méthodologie conçue pour comprendre les variables/fonctions écologiques et leur dynamique à différentes échelles spatiales. Le but de cette étude est d'évaluer la capacité des techniques de diffraction des rayons X (XRD) pour prédire rapidement les propriétés fonctionnelles du sol et développer des fonctions de pédo-transfert pour les sols de l'Afrique. Les échantillons géo-référencés associés au Service d'information des sols en Afrique (AfSIS), pris à partir d'un ensemble de sites sentinelles randomisés sur l'Afrique sub-saharienne ont été utilisées pour la caractérisation. Un total de 160 échantillons de sol de la surface provenant de 16 points aléatoires de dix sites de 100-km2: Tanzanie (3 sites), Malawi (2 sites), Mali (1 site), Burkina Faso (1 site), Kenya (2 sites) et Ghana (1 site) ont été caractérisés pour les propriétés chimiques, la distribution des tailles des particules, les propriétés mécaniques et la minéralogie en volume. La variation de la minéralogie à l'intérieur et entre les sites a été explorée en utilisant une analyse multivariée, y compris l'analyse de la composante principale dans le logiciel statistique R, comme un précurseur à l'exploration des relations avec les propriétés du sol mesurées directement et les diagnostics de fertilité des sols. Le regroupement des minéraux individuels et les distributions des variables de fertilité des sols identifiées à travers les sites semblaient se rapporter à des différences dans les groupes fonctionnels minéralogiques, en soutenant la compréhension des différences et des similitudes de l'environnement pédologiques. Les résultats ont présenté par conséquent la possibilité d'améliorer l'évaluation des sols en utilisant les informations sur la minéralogie du sol. Par exemple les informations DRX sur la minéralogie peuvent être combinées avec des informations de la spectroscopie infrarouge, qui caractérisent les propriétés minérales et physico-chimiques du sol, pour offrir des capacités puissantes de diagnostic, et peuvent être utilisées comme une entrée complémentaire aux fonctions de pédo-transfert pour un faible coût et la prédiction rapide des propriétés fonctionnelles du sol.

Mots clés: Sols d'Afrique, surveillance de diagnostic, spectroscopie infrarouge, analyse multivariée, fonctions de pédo-transfert, fertilité des sols, minéralogie du sol, diagnostics spectraux, diffraction des rayons X

Background

More than 70 % of Africa's rural poor depend on agriculture for their livelihoods. The fate of agricultural production, therefore directly affects economic growth, social improvement and trade in Africa. Africa's soils are important for food production to feed the rapidly growing population. Apart from food production, inadequate soil management has serious consequences for other natural resource essentials to Africa's livelihoods and development. Soil provides essential ecosystem services and plays a key role in sustaining them. For example, soils are key resources in the production of foliage, fuel and fibre. Soils store and cycle water from irrigation, filter toxic substances through clay sorption and precipitation process that determine surface and ground water quality. Soil organisms on the other hand decompose organic materials, cycle nutrients and regulate gas fluxes to and from the atmosphere. Other benefits people obtain from ecosystems include provision of services that affect climate, pests and diseases; supporting services such as soil formation and photosynthesis; and cultural services (Smaling, 1998; Millennium ecosystem assessment, 2005).

Soil health is often described as an integrative property that reflects the capacity of soil to respond to agricultural intervention, so that it continues to support both the agricultural production and the provision of other ecosystem services (Kibblewhite *et al.*, 2008). It is often used to describe the general condition of the soil resource base in the context of agricultural management and intervention. Soil health surveillance is built around new approaches to soil analysis which emphasizes measurement of soil functional properties that determine soil health – the capacity of land to sustain delivery of essential functions or ecosystem services, such as hydrological regulation, nutrient supply to plants and nutrient retention, and defining these properties according to the degree to which they are dynamic and to which they are influenced by management (Swift and Shepherd, 2007; Robinson *et al*., 2009). Combining these new approaches with modern analytical techniques allows for an integrative analysis of soil chemical and physical properties and the development of a holistic analysis of soil condition. For example, variables affecting soil nutrient capacity such as clay mineralogy, total elemental concentrations, absorbance spectra, texture and parent material can be combined to provide a more accurate assessment of soils' nutrient capacity. One such technique is the use of X-ray diffraction (XRD) to analyse soil mineralogy.

Soil mineralogy is the study of the solid inorganic phases controlling the physio-chemical processes in soils and is key in the determination of basic soil functional properties and is one of the principal soil forming factors (Jenny, 1941). Soil mineralogy has a profound influence on the dynamic behavior of soils namely the gains, losses, transformation and translocation. Understanding mineralogy of the soil has important implications for assessing functional soil properties, such as interactions with nutrients, heavy metals, inorganic and organic contaminants, and biological compounds. These include Al toxicity, sorption of metals, organics and nutrients to mineral surfaces, nutrient quantity (stock) and availability (intensity or strength of retention by soil), fertiliser response, water storage, erosion susceptibility, organic matter retention and provision of sites for microbial and faunal activities. These properties in turn determine soil agricultural, environmental and engineering qualities.

Study Description

The African Soil Information Services (AfSIS) has developed a practical, timely and cost-effective soil health surveillance system to improve the assessments of soil conditions, enable mapping of soil functional properties, set a baseline for monitoring changes, and provide options for improved soil and land management. The system is facilitating the identification of areas at risk of soil degradation and corresponding preventive and rehabilitative soil management interventions. AfSIS builds on recent advances in digital soil mapping, infrared spectroscopy, remote sensing, statistical analysis, and integrated soil fertility management (ISFM), an approach that has presented the opportunity to improve soil assessments using information on soil mineralogy. This study builds on AfSIS. Geo-referenced samples associated with the Africa Soil Information Service (AfSIS) (www.africasoils.net), taken from a set of sentinel sites stratified by climate and randomised over sub-Saharan Africa were used for soil characterisation.

A total of 160 top soil samples taken from16 randomised sample points at each ten 100 km^2 sites across sub-Saharan Africa: Tanzania (3 sites), Kenya (2 sites), Ghana (1 site), Mali (1 site), Burkina Faso (1 site), Malawi (2 sites) were used for reference analysis using the AfSIS standard soil fertility module measurement methods. Soils were air-dried and crushed to pass through a 2-mm sieve. Soil fines were finely ground to less than 75 micron. These were used for organic carbon analysis. The remaining soil fines were used for physico-chemical and mineralogical analysis. XRD analysis were done using a Bruker benchtop, D2 phaser diffractometer system with Ni-filtered, Cu-Ká radiation (30 kV and 10 mA) using a 0.6 mm divergence slit, a 1mm anti-scatter slit, and a 2.5 mm axial solar slits. The XRD patterns were recorded at a variable rotation of 15^o/min in the angular measurement range of 3 to 75^o 2Theta with a 0.02^o accuracy and at 0.5 sec/step (Fig 2). Samples for bulk mineralogy analysis were further prepared by wet milling in a McCrone micronising mill and then mounted onto low background sample holders using the razor tampered surface (RTS) method. These procedures aimed at achieving the optimal conditions for preparation, deposition and measurement in XRD analysis. We explored the variation of the mineralogy within and between sites using principal component analysis in R statistical software as a precursor to exploring relationships with directly measured soil properties.

Results and Discussion

Using multivariate methods, including principal component analysis we characterised and classified the physico-chemical and the mineralogical data from the soils collected across the ten locations, enabling us to recognise geologic controls and soil forming processing, including soil parent material, weathering and soil age. All soils exhibited a wide range of relationships between the physico-chemical and mineralogical properties. The clustering of individual minerals and the distribution of the soil fertility variables identified across the sites appeared to relate to differences in mineralogical functional groups, supporting the understanding of the pedologic environment differences and similarities. The uniqueness of the signatures for the physico-chemical properties and the mineralogy data of soils from all ten locations emphasized the control exerted by weathering effects. These relationships demonstrated the potential that determination of soil mineralogy using X-ray diffraction technique can allow for the determination and prediction of soil functional properties such as water holding capacity, organic matter retention, soil nutrients, fertiliser response among others.

Research Application

The findings present opportunity to improve soil assessment using information on soil mineralogy. For instance XRD information on mineralogy can be combined with information from infrared spectroscopy, which characterises soil mineral and physio-chemical properties, to provide powerful diagnostic capabilities, and be used as a complementary input to pedo-transfer functions for low cost and rapid prediction of soil functional properties. Prediction accuracy would allow the use of MIR spectroscopy together with mineralogical within the framework of soil fertility diagnostics and evaluation; the ability of soils to provide, at the right time, essential plant nutrients in adequate amounts and suitable proportions to sustain plants growth. This approach provides future data analysis framework for interpreting the physico-chemical and mineralogical processes in soils and will be used for evaluating the AfSIS project that is currently underway. Our research would be strengthened by conducting quantitative mineralogical analysis.

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