Are environmental conditions predisposing to calcium-deficiency rickets in developing countries?
A community-based case study from rural Kaduna, northern Nigeria

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Zusammenfassung

Einleitung. Kalziummangel-Rachitis (*calcium-deficiency rickets*, CDR) ist eine Knochenerkrankung bei Kindern, die sich durch einen starken Mangel an Ca im Blutserum, eine gestörte Mineralisierung sowie Verformungen der Knochen äußert. Die Erkrankung ist seit ca. 30 Jahren bekannt und ist vor allem in tropischen Ländern wie Bangladesch, Gambia, Nigeria oder Südafrika vorzufinden. Verbreitungsraten von 4% bis 9% sind heutzutage in bestimmten Regionen dieser Länder keine Seltenheit mehr und deuten darauf hin, dass CDR zu einem weit verbreitetem Gesundheitsproblem in Entwicklungsländern heranwachsen könnte. Bisherige Forschungsarbeiten zu den Ursachen von Hypokalzämie und CDR in Entwicklungsländern beschränken sich fast ausnahmslos auf biochemische, genetische, ernährungswissenschaftliche und sozioökonomische Untersuchungen. Der Auslöser der Erkrankung konnte in diesen Studien jedoch bisher nicht eindeutig identifiziert werden.

Da CDR schwerpunktmäßig aus tropischen Ländern bekannt ist und dort oftmals als endemische Erkrankung vorkommt, wird derzeit diskutiert ob Umweltfaktoren eine Rolle in der Ätiologie der Erkrankung spielen könnten. Neben einem Mangel an bestimmten Makronährstoffen und Mikronährstoffen im Pfad Boden-Pflanze, welcher charakteristisch für viele tropische Gebiete ist, könnte auch ein Überangebot bestimmter potentiell toxischer Elemente (*potentially toxic elements*, PTEs) in den Ökosystemen von CDR-Gebieten ein möglicher Auslösefaktor der Knochenerkrankung sein. Da ein Großteil der lokalen Bevölkerung in Entwicklungsländern von Subsistenzlandwirtschaft lebt, ist es möglich, dass solche Element-Anomalien direkt an den Menschen weitergegeben werden, was schließlich auch eine Gefahr für die Gesundheit der Knochen darstellt.

Derartige Umwelt-Mensch-Zusammenhänge sind bereits aus anderen Regionen der Erde bekannt. So wird beispielsweise in China die endemische Kashin-Beck-Erkrankung auf einen Mangel an Se im anstehenden Gestein und in den Böden zurückgeführt. In Maputaland in Südafrika wird die endemisch auftretende Mseleni-Joint Knochenerkrankung mit einem homogenen Mineralspektrum im anstehenden Gestein und einem daraus folgenden Mangel an Makronährstoffen und Mikronährstoffen in den Böden in Zusammenhang gebracht. In anderen Regionen der Welt, wie beispielsweise in Tansania oder Indien, ist es möglich, dass ein Überangebot an F im anstehenden Gestein, in den Böden und im Trinkwasser der Auslöser von Skelettfluorose ist. Obwohl ähnliche Zusammenhänge auch für die CDR-Gebiete in Entwicklungsländern gelten könnten, wurden bisher keine tiefer gehenden Studien über den Zusammenhang zwischen Umweltbedingungen und CDR-Knochenerkrankung durchgeführt.

Die hier vorliegende Arbeit ist die erste umfassende wissenschaftliche Studie, welche den Einfluss von Umweltfaktoren auf die Knochenerkrankung CDR untersucht. Sie überprüft die Hypothese, ob ein Mangel an Makronährstoffen und Mikronährstoffe, bzw. ein Überangebot bestimmter PTEs im Gestein, in den Ausgangssubstraten, Böden, Trinkwasser oder den pflanzlichen Nahrungsmitteln CDR in einer ländlichen Region nahe Kaduna Stadt, Nordnigeria, ausgelöst haben kann. Sollte ein vergleichbarer Mangel an Makronährstoffen

und Mikronährstoffen bzw. ein vergleichbares Überangebot bestimmter PTEs gleichermaßen auch in den Ökosystemen anderer CDR-Gebiete zu finden sein, so wurde in einer zweiten Hypothese angenommen, ist ein genereller Zusammenhang zwischen Umweltbedingungen und CDR in Entwicklungsländern möglich.

Materialien und Methoden. Um den Einfluss von Umweltfaktoren auf die Verbreitung von CDR in Entwicklungsländern zu untersuchen, wurde ein ländliches Gebiet von 2500 km² in der Nähe von Kaduna Stadt, Nordnigeria, als Untersuchungsgebiet gewählt. Aus dieser Region ist seit Beginn der 2000er Jahre eine starke Häufung von Rachitisfällen mit einer Verbreitungsrate von 5% bekannt. Innerhalb dieses Untersuchungsgebietes wurden 11 Untersuchungsstandorte aufgesucht, die in Gebiete mit einer hohen Rachitisprävalenz (*high risk*, HR), Gebiete mit einer niedrigen Rachitisprävalenz (*low risk,* LR) und Gebiete ohne Rachitis (*no risk,* NR) aufgeteilt wurden.

In diesen HR-, LR- und NR-Untersuchungsstandorten wurden die geochemischen Eigenschaften, das Gefüge und die Mineralzusammensetzung des anstehenden Gesteins analysiert, sowie die eigentlichen Ausgangssubstrate der Bodenbildung bestimmt. Die Intensität der Landnutzung, die Arten der Feldfrüchte, die Mengen und Typen verwendeter Düngemittel sowie die Intensität industrieller Nutzung wurden mittels offener Befragungen der lokalen Kleinbauern abgeschätzt. Die Bodentypen wurden entlang von Catenen und nach dem Bestimmungsschlüssel der *World Reference Base for Soil Resources* (WRB) klassifiziert. Die typische Verbreitung der Böden wurde mittels eines bodengeographischen Ansatzes auf das gesamte Untersuchungsgebiet übertragen. In Laboruntersuchungen wurde die Textur der Böden mittels Pipette und Siebung bestimmt und die Zusammensetzung der Tonfraktion durch Röntgendiffraktometrie analysiert. Die pH-Werte wurden in KCl-Lösung gemessen und die Gehalte an organischem Kohlenstoff (OC) mittels nasser Veraschung bestimmt. Die potentielle Kationenaustauschkapazität (CECpot), die Basensättigung (BS) sowie die pflanzenverfügbaren Anteile an Ca und Mg wurden in einer $BaCl_2$-Lösung gemessen. Die pflanzenverfügbaren Konzentrationen an K und P wurden in einem Ca-Acetat-Lactat-Auszug bestimmt. Die Gehalte an Mikronährstoffen, welche die Elemente Cu, Se und Zn beinhalteten, wurden mittels Königswasserextraktion gemessen. Die Gehalte an wasserlöslichem Se wurden in entionisiertem Wasser bestimmt. Die Gehalte an PTEs, bestehend aus den Elementen Al, Fe, Cd, Pb, und Sr wurden mittels Königswasserextraktion ermittelt. Die Gesamtgehalte an F wurden in einer NaOH-Lösung und die säurelöslichen Gehalte an F mittels HCl-Extraktion bestimmt. Zur Abschätzung des Komplexierungspotentials einzelner Elemente im Boden wurden Spearman's Rank Korrelationskoeffizienten berechnet. Darüber hinaus wurden Trinkwasserproben auf pH-Werte untersucht sowie die Gehalte an Ca, Se und F kolorimetrisch bzw. spektrometrisch gemessen. In Mais wurden die Gehalte an Ca, Mg, K und P nach Salpetersäure-Extraktion und die Gehalte an Se und Phytinsäure (PA) in einer HCl-Lösung bestimmt.

Die gemessenen Elementgehalte in den Umweltproben der HR-, LR- und NR-Untersuchungsstandorte wurden miteinander verglichen sowie in Bezug auf nationale Hintergrundwerte (*background values*) und internationale Grenzwerte (*critical limits*) betrachtet. Darüber hinaus wurden die Laborergebnisse dieser Studie mit den Umweltbedingungen in anderen Gebieten mit endemischen Knochenerkrankungen, wie Kashin-Beck-Erkrankung, Mseleni-Joint-Erkrankung und Skelettfluorose, vergleichend betrachtet. Um den Einfluss von Umweltfaktoren auf CDR nicht nur auf der lokalen Ebene, sondern auch auf globaler Ebene bewerten zu können, wurde Literatur über die Umweltbedingungen anderer CDR-Gebiete in Bangladesch, Gambia, Nigeria und Südafrika herangezogen und in Hinblick auf die Ergebnisse aus der Kaduna-Region ausgewertet.

Ergebnisse und Diskussion. Die Feld- und Laboruntersuchungen am anstehenden Gestein zeigten, dass die HR-, LR- und NR-Untersuchungsstandorte nahe Kaduna Stadt von Graniten unterlagert sind, welche dem Typ *Older Granites* zuzuordnen sind. Da die Older Granites nicht nur in den HR- und LR-Untersuchungsstandorten, sondern auch einem NR-Untersuchungsstandort identifiziert wurden, wurde ein direkter Zusammenhang zwischen der Verbreitung der *Older Granites* und der Verbreitung von CDR als unwahrscheinlich erachtet. Dünnschliff-Untersuchungen zeigten darüber hinaus, dass die *Older Granites* relativ hohe Gehalte an Nährstoff- und F-reichen Mineralien aufweisen, weswegen eine natürlich bedingte Nährstoffarmut in den Böden der Region als fraglich, ein F-Überangebot indes als möglich eingestuft wurde. Die eigentlichen Ausgangssubstrate der Bodenbildung stellen in allen Untersuchungsstandorten grushaltige Lockersedimentdecken, pisolithaltige Lockersedimentdecken sowie Auensedimente dar, welche nachweisbare Mengen an äolischen Ablagerungen enthalten. Ein Zusammenhang zwischen der Verbreitung der verschiedenen Ausgangssubstrate der Bodenbildung und den CDR-Prävalenzraten konnte nicht festgestellt werden.

Interviews mit den Kleinbauern der Region machten deutlich, dass die Landnutzung vom Anbau von Nutzpflanzen geprägt ist, die einerseits für den Verkauf produziert werden (*cash crops*), aber auch der Ernährung der lokalen Kleinbauernfamilien dienen (*food crops*). Das Grundnahrungsmittel in der Kaduna-Region ist Mais (*Zea mays*). Basierend auf einem Bevölkerungswachstum von 4% seit der 1970er Jahre und einem daraus resultierenden gestiegenen Bedarf an Nahrungsmitteln werden in der Kaduna-Region zunehmend mehr Landanteile für den Anbau von Nahrungsmitteln genutzt. Gleichzeitig werden Dünge- und Pflanzenschutzmittel aufgrund der allgemeinen Verarmung der lokalen Bevölkerung nur in sehr geringen Mengen verwendet. Ein anthropogen induzierter Mangel an Makronährstoffen und Mikronährstoffen in den Ökosystemen der Kaduna-Region wurde daher als denkbar eingestuft. Eine übermäßige industrielle Nutzung konnte in keinem der Untersuchungsstandorte festgestellt werden. Es wurde somit angenommen, dass der anthropogene Eintrag bestimmter PTEs in die Ökosysteme des Untersuchungsgebietes gering ist.

Felduntersuchungen zu den Bodentypen des Untersuchungsgebietes zeigten, dass die Bodenvergesellschaftung in der Kaduna-Region eng mit der Topographie und der Verbreitung der verschiedenen Lockersedimentdecken verknüpft ist. In nächster Nähe zu den Inselbergen und auf grushaltigen Lockersedimentdecken finden sich Lixisole. In den unteren Bereichen der Inselberg-Pedimente sowie in Niederungen der Rumpfflächen haben sich aus grus- oder aus pisolithaltigen Lockersedimentdecken Acrisole entwickelt. Auf den Rumpfflächen, insbesondere in Gebieten in denen pisolithaltige Lockersedimentdecken das Ausgangssubstrat bilden, sind Plinthosole der dominierende Bodentyp. In den Randbereichen kleinerer Flüsse, in denen Auensedimente das Ausgangssubstrat bilden, haben sich Fluvisole entwickelt. Derartige Bodengesellschaften sind typisch für Granit-dominierte Regionen der nördlichen Guinea-Savanne in Westafrika.

Auch die physikalischen Bedingungen der Böden in der Kaduna-Region sind repräsentativ für die nördliche Guinea-Savanne: sandige Oberböden, tonige Unterböden und relativ hohe Gehalte an Kaolinit in der Tonfraktion. Verglichen mit den durchweg sandigen Böden in Maputaland, Südafrika, die von der an Mseleni-Joint-Erkrankung betroffenen lokalen Bevölkerung zum Anbau von Feldfrüchten genutzt werden, weisen die Böden der Kaduna-Region eine sehr heterogene Textur auf.

Auch in Hinblick auf die geochemischen Eigenschaften der Böden wurde kein signifikanter Unterschied zwischen den Böden der Kaduna-Region und den Böden anderer Granit-dominierter Gebiete in Westafrika festgestellt. Untersuchungen zu den pH-Werten sowie zu den Gehalten an OC, CECpot, BS, Ca, Mg, K und P zeigten, dass in den Böden des Untersuchungsgebietes nur die Gehalte an P sehr niedrig sind. Ein Mangel an P ist jedoch ein normales Phänomen für Böden in westafrikanischen Savannen und ist nicht auf Gebiete mit CDR-Erkrankung beschränkt.

Auch die Gesamtgehalte an Se und Zn sind, im Vergleich zu nationalen Hintergrundwerten, in normalen Konzentrationen in den Böden des Untersuchungsgebietes vorhanden. Allein die Gesamtgehalte an Cu und die wasserlöslichen Konzentrationen an Se sind in den Böden der Kaduna-Region nachweislich niedrig. Vergleiche zu internationalen Grenzwerten zeigten jedoch, dass die Konzentrationen an wasserlöslichem Se nicht kritisch niedrig und die Gesamtgehalte an Cu nur in den Böden eines LR-Untersuchungsstandortes kritisch niedrig sind. Im Vergleich zu Gebieten mit Mseleni-Joint bzw. Kashin-Beck-Erkrankung weisen die Böden im Untersuchungsgebiet nahe Kaduna deutlich höhere pflanzenverfügbare Gehalte an Makronährstoffen und Mikronährstoffen auf. Eine Komplexierung zwischen bestimmten Bodenparametern, welche die Verfügbarkeit von Makronährstoffen und Mikronährstoffen zusätzlich erschweren könnte, konnte in den Böden des Untersuchungsgebiets nicht festgestellt werden.

Laboruntersuchungen zu den Gehalten an PTEs in den Böden zeigten, dass die Gesamtgehalte an Al, Fe, Sr, Cd, Pb und F, verglichen mit weltweiten Hintergrundwerten und internationalen Grenzwerten, in den Böden der Kaduna-Region sehr niedrig sind. Im Vergleich zu Gebieten in denen Skelettfluorose endemisch auftritt, sind die Gesamt- und wasserlöslichen Gehalte an F in den Böden der Kaduna-Region hoch genug, um die Härtung der Knochen zu unterstützen, jedoch zu niedrig, um einen potentiell schädigenden Einfluss auf die Knochengesundheit der lokalen Bevölkerung zu haben.

Auch im Trinkwasser konnte weder ein auffälliger Mangel an Makronährstoffen und Mikronährstoffen noch ein deutliches Überangebot bestimmter PTEs festgestellt werden. Niedrigste pH-Werte und Ca-Gehalte weist das Trinkwasser in den HR-Untersuchungsstandorten auf, wohingegen das Trinkwasser in den LR- und NR-Untersuchungsstandorten die niedrigsten Gehalte an Se und die höchsten Konzentrationen an F enthält. Verglichen mit Grenzwerten der Weltgesundheitsorganisation (WHO), sind die Gehalte an Ca und Se im Trinkwasser aller Untersuchungsstandorte ausreichend und die Gehalte an F im Normalbereich. Es konnte kein statistisch signifikanter Unterschied zwischen den Elementkonzentrationen in Grund- und Oberflächenwasser festgestellt werden. Im Vergleich zu den mittleren Gehalten an Se im Trinkwasser von Kashin-Beck-Gebieten sind die Gehalte an Se im Trinkwasser der Kaduna-Region vergleichsweise niedrig, jedoch nicht kritisch niedrig. Die Gehalte an F hingegen sind deutlich niedriger als in Gebieten mit endemischer Skelettfluorose, weswegen ein Einfluss von F im Trinkwasser der Kaduna-Region auf die Verbreitung von CDR in der Kaduna-Region als sehr unwahrscheinlich eingestuft wurde.

Der Mais in den HR-, LR- und NR-Untersuchungsstandorten der Kaduna-Region weist, verglichen mit westafrikanischen Nährwerttabellen (*food composition tables*), normale Gehalte an Mg, K und P, geringe Konzentrationen an Ca und Se sowie leicht erhöhte Gehalte an Phytinsäure (PA) auf. Vergleiche zwischen den Mineralanteilen von traditionellen und modernen Maissorten zeigten, dass die traditionellen Maissorten, welche seit den 1960er Jahren in der Kaduna-Region nur noch vereinzelt angebaut werden, deutlich höhere Gehalte an Ca und deutlich niedrigere Gehalte an PA aufweisen als die modernen Maissorten. Dies legt die Vermutung nahe, dass der Wechsel, weg von relativ nährstoffreichen traditionellen Getreidesorten und hin zu nährstoffärmeren und PA-haltigeren Hybridsorten eine negative Auswirkung auf die gesamte Nährstoffversorgung der lokalen Bevölkerung, und somit auch Einfluss auf die Prävalenz von CDR gehabt haben könnte.

Im Vergleich zu den Ergebnissen aus der Kaduna-Region zeigte eine Literaturauswertung zu den Umweltbedingungen in CDR-Gebieten in Bangladesch, Gambia, Nigeria und Südafrika, dass die anstehenden Gesteine sowie die Ausgangssubstrate der Bodenbildung in diesen Regionen teilweise potentiell arme, teilweise aber auch potentiell reiche Mineralspektren aufweisen. Die meisten dieser CDR-Gebiete befinden sich in Flachländern in denen sich Bodentypen mit hoher Bodenfruchtbarkeit aber auch Bodentypen mit einem sehr begrenzten Nährstoffpotential entwickelt haben. Die Gehalte an Makronähstoffen, Mikronährstoffen und PTEs in dem Trinkwasser und den Nahrungsmitteln liegen in diesen CDR-Gebieten, verglichen mit Grenzwerten der WHO sowie nationalen Nährwerttabellen, stets im Normalbereich. In allen CDR-Gebieten, inklusive der Kaduna-Region, ist ein Ernährungswandel hin zu einer sehr einseitigen, mikronährstoffarmen Ernährung evident, die im steigenden Maße arm an Fleisch und Milchprodukten ist und auf dem Anbau und Konsum von ertragreichen Getreidesorten basiert.

Schlussfolgerungen. Ein Zusammenhang zwischen den Umweltbedingungen und der Prävalenz von CDR in der Kaduna-Region wurde als unwahrscheinlich eingestuft. Dies begründet sich darin, dass Gestein, Ausgangssubstrate, Böden und Trinkwasser im Untersuchungsgebiet, im Vergleich zu nationalen Hintergrundwerten bzw. internationalen Grenzwerten, keine signifikant niedrigen Makro- und Mikronährstoffgehalte aufweisen. Darüber hinaus konnten in den Umweltproben der Kaduna-Region auch keine auffällig hohen Gehalte an PTEs festgestellt werden. Im Mais hingegen wurden allgemein niedrige Gehalte an Ca und Se sowie erhöhte Konzentrationen an PA gemessen, welche jedoch vermutlich nicht umweltbedingt sondern sortenbedingt sind. Darüber hinaus zeigten Vergleiche zwischen modernen und traditionellen Maissorten, dass die modernen Maissorten signifikant niedrigere Gehalte an Ca und signifikant höhere Gehalte an PA aufweisen als die traditionellen Sorten. Es wurde daher angenommen, dass die Umstellung von traditionellen, Ca-haltigen und PA-armen Maissorten hin zu einem steigenden Anbau von modernen, Ca-armen und PA-reichen Maissorten zu einem Mangel an Ca in der Ernährung, und damit auch zu einem Mangel an Ca in der lokalen Bevölkerung geführt haben könnte.

Die Umweltbedingungen in den CDR-Gebieten in Bangladesch waren, im Vergleich zu denen der Kaduna-Region, sehr unterschiedlich, wohingegen die Umweltbedingungen in den CDR-Gebieten in Gambia und Südafrika teilweise ähnlich zu denen der Kaduna-Region waren. Ein genereller Zusammenhang zwischen Umweltbedingungen und CDR in Entwicklungsländern wurde daher als unwahrscheinlich eingestuft. Hingegen zeigte sich, dass ein Wandel in der Auswahl der Kulturpflanzensorten, welcher bereits in der Kaduna-Region identifiziert wurde, auch in anderen CDR-Gebieten in Entwicklungsländern vorzufinden ist. Es wurde daher geschlussfolgert, dass eher die Ernährung als die Umweltbedingungen der Auslöser von CDR in Entwicklungsländern ist.

Ausblick. Um den Einfluss von Umweltfaktoren auf die Erkrankung von CDR endgültig ausschließen zu können, ist weitere Forschung zu den Anteilen an Makronährstoffen und Mikronährstoffen sowie PTEs in den Ökosystemen anderer CDR-Gebiete in Entwicklungsländern nötig. Diese sollten insbesondere auf deren pflanzenverfügbaren Anteile untersucht werden. Darüber hinaus sollten sich künftige Forschungsarbeiten der Bestimmung jener Getreidesorten widmen, die in CDR-Gebieten zum eigenen Konsum angebaut werden. Von Interesse ist es dabei auch, deren Gehalte an Makronährstoffen, Mikronährstoffen und PAs zu quantifizieren und diese vergleichend zu betrachten. In Kombination mit ernährungswissenschaftlichen Studien zu den traditionellen bzw. modernen Ernährungsweisen in CDR-Gebieten ließe sich hierdurch noch genauer abschätzen, welchen Einfluss der Wandel in den Hauptgetreidesorten und Ernährungsweisen auf die Prävalenz von CDR in Entwicklungsländern hat. Insbesondere gegen Ende der Trockenzeit ist das Nahrungsangebot in Entwicklungsländern stark eingeschränkt. Untersuchungen zu den Geburtsmonaten von CDR-Kindern könnten darüber Aufschluss geben, ob eine saisonal bedingte Nahrungsknappheit bzw. einseitige Ernährung der Mütter ein prädisponierender Faktor für die Erkrankung ihrer Kinder an CDR ist. In Zeiten klimatischer Veränderungen sowie unter steigendem demographischen Druck könnten sich derartige Nahrungsmittelknappheiten noch mehr verschärfen. Eine weitere Erforschung dieser Hypothesen könnte sowohl dazu beitragen Lösungsmöglichkeiten für die steigenden CDR-Fallzahlen zu finden, als auch Bewusstsein für die Wichtigkeit von ausgewogener Ernährung schaffen, und somit langfristig die Ernährungssituation in Entwicklungsländern verbessern.

Summary

Introduction. Calcium-deficiency rickets (CDR) is a metabolic bone disease in children that is characterized by a lack of Ca in the blood, impaired mineralization and severe bone deformities. The disease first became known some 30 years ago and is predominantly found in tropical countries, such as Bangladesh, Nigeria, South Africa and The Gambia. Nowadays, prevalence rates between 4 and 9% are not uncommon in some areas of these countries, which indicates that CDR is on the increase in developing countries. Previous research on the cause of hypocalcaemia and CDR in developing countries was almost entirely focused on biochemical, genetic, nutritional and socio-economic analyses. However, the cause of the disease is still unknown.

As CDR is often an endemic phenomenon that is almost exclusively restricted to tropical areas, environmental conditions are currently considered to be a possible predisposing factor for the CDR in developing countries. Apart from a lack of specific macronutrients and micronutrients, an oversupply of potentially toxic elements (PTEs) in the soil-plant pathway of the different CDR areas is also thought to be involved in the aetiology of CDR. As most people in developing countries live on subsistence farming, element anomalies in the environment may be particularly intense and may therefore affect bone health.

Such environment-human interactions are already known from other parts in the world. A classical example of an endemic bone disease that has been associated with environmental conditions is Kashin-Beck disease in China, where a lack of Se in bedrock and soils is assumed to have caused Se-deficiency-induced bone deformities. Furthermore, in Maputaland in South Africa, endemic cases of Mseleni joint disease are assumed to be caused by a homogeneous bedrock mineral spectrum and thus, a lack of macronutrients and micronutrients in the soils. In other regions of the world, including developing countries such as Tanzania or India, an oversupply of F in the bedrock, soils and drinking water is known to cause skeletal fluorosis. Although similar relationships may also be found in the CDR areas of developing countries, detailed studies have yet not been made on the link between environmental conditions and the prevalence of CDR.

This study is the first to comprehensively analyse the impact of the environment on Ca deficiency and the resulting CDR. The study investigates the hypothesis whether a lack of macronutrients and micronutrients or an oversupply of PTEs in the bedrock, parent materials, soils, drinking water or the crop plants has caused CDR in a rural area near Kaduna City, northern Nigeria. A general link between environmental conditions and CDR was assumed to be most probable if a lack of macronutrients and micronutrients as well as an oversupply of PTEs could also be found in the environment of other CDR areas in developing countries.

Materials and methods. To analyse the impact of the environment on CDR in developing countries, a 2500-km² rural region near Kaduna City, northern Nigeria, was chosen as a study area. From this area, cases of CDR have been reported since the early 2000s with a

prevalence rate of 5%. Within this study area, 11 study sites, including areas with a high CDR prevalence (HR), a low CDR prevalence (LR) and no CDR prevalence (NR), were visited. In these HR, LR and NR study sites, the bedrock was investigated for structure, mineral composition and geochemical composition and the types of parent materials were identified. Local farmers were interviewed to determine the type and intensity of the land use, the crop varieties as well as the types and amounts of fertilizers used. The soil types were determined along toposequences, using the World Reference Base for Soil Resources (WRB) classification system. The distribution of the soils over the Kaduna study area was modelled on the basis of a soil-geographical approach. The soil texture was determined by pipette and sieving, and the clay mineral fractions were analysed by X-ray diffractometry. The pH values were measured in KCl solution, and the contents of organic carbon (OC) were determined by wet combustion. The potential cation-exchange capacity (CECpot), the base saturation (BS) as well as the plant-available concentrations of Ca and Mg were extracted by $BaCl_2$. The plant-available concentrations of K and P were measured in Ca-acetate-lactate solution. The micronutrient concentrations, including Cu, Se and Zn were determined after aqua regia extraction. The concentrations of water-soluble Se were measured in deionized water. Furthermore, the PTE concentrations, including Al, Fe, Cd, Pb and Sr, were determined in aqua regia. The concentrations of total F were determined after NaOH extraction and the acid-soluble F concentrations were measured in HCl solution. To estimate the complexing potential between certain soil elements, Spearman's rank correlation coefficients were calculated. The drinking water was analysed for pH values and the concentrations of Ca, Se and F were measured both colorimetrically and spectrometrically. The maize was analysed for the Ca, Mg, K and P concentrations by using nitric acid (HNO_3) extraction and the Se and phytic acid (PA) contents were determined in HCl solution.

The measured concentrations of these elements in the bedrock, soil, drinking water and maize were compared between the HR, LR and NR study sites. Comparisons were also made to national background levels as well as international critical limits. Furthermore, the results of this study were compared to the environmental conditions of areas with other bone diseases, including Kashin-Beck disease, Mseleni joint disease and skeletal fluorosis. In order to assess the impact of the environment on the CDR not only locally but also on a global scale, a review of the environmental conditions of other CDR areas in developing countries was conducted, including CDR areas in Bangladesh, Nigeria, South Africa and The Gambia. The laboratory and review results were compared to each other.

Results and discussion. The field and laboratory analyses on the bedrock showed that the HR, LR and NR study sites near Kaduna City, northern Nigeria, were underlain by Older Granites. A direct link between the distribution of the granitoid bedrock and the prevalence of CDR was not found. Thin-section analyses showed that the Older Granites contained relatively high amounts of nutrient- and F-rich minerals, meaning that a nutrient deficiency in soil due to a mineral-poor bedrock type is unlikely, while an oversupply of F in the soils of the study area was assumed to be possible. The actual parent materials of the soil formation in the Kaduna study area were grus slope deposits, pisolite slope deposits and river deposits, which comprised considerable amounts of aeolian deposits. No link was found between the distribution of the parent materials and the CDR prevalence rates in the Kaduna study area.

Interviews with the local farmers showed that the land use in the Kaduna study area is dominated by the cultivation of cash crops and food crops. The staple crop in the Kaduna study area is maize (*Zea mays*). Based on a population growth rate of 4% among the population of the Kaduna study area since the 1970s and the resulting increased need for food, the land percentages used for agricultural land use were reported to have steadily increased in the Kaduna study area. However, as a consequence of poor economic conditions, fertilizers and plant-protection products were used only in small amounts. Thus, an anthropogenically caused lack of macronutrients and micronutrients in the ecosystems of the Kaduna study area was considered likely. In contrast, an excessive industrial use was not identified in the study sites, indicating that an anthropogenic input of PTEs in the local ecosystems of the Kaduna study area was unlikely.

Field analyses on the soil types in the Kaduna study area showed that the distribution of the soil types is highly dependent on the topography and the distribution of the parent materials. In near vicinity to the inselbergs, Lixisols had developed on grus slope deposits. In the lower pediment and plain positions, Acrisols had developed on grus slope deposits and pisolite slope deposits. In the upper plains, Plinthosols had developed on pisolite slope deposits and in the river valleys, Fluvisols had developed on river deposits. Such soil types and soil type distributions are typical for granite-underlain areas in the northern guinea savanna of West Africa.

Similarly, the physical soil conditions were representative for the soils of the northern guinea savanna: sandy topsoils, clayey subsoils and relatively high contents of kaolinite clay minerals in the clay fractions. Compared to the overall sandy soils in Maputaland in South Africa, which are agriculturally used by the local Mseleni-joint-disease impacted population, the soils of the Kaduna study area had a heterogeneous soil texture.

With regard to the geochemical composition, no significant difference was found between the soils of the Kaduna study area and the soils of other granite-underlain areas in West Africa. Analyses on the pH values as well as the concentrations of OC, CECpot, BS, Ca, Mg, K and P showed that only the concentrations of P were considerably low in the soils of the Kaduna study area. However, P deficiency is a typical phenomenon in West African savanna soils and is not restricted to CDR areas.

The concentrations of total Se and total Zn in the soils of the Kaduna study area were within safe ranges, while the total Cu and water-soluble Se concentrations were low compared to Nigerian background values. Comparisons to international critical limits showed that the concentrations of water-soluble Se were low, but not critically low, and that the contents of total Cu were critically low only in a LR study site. The soils in the Kaduna study area contained significantly higher concentrations of plant-available macronutrients and micronutrients than the soils in areas of endemic Mseleni joint disease in South Africa and the soils in areas of endemic Kashin-Beck disease in China. A complexation between certain trace elements and minerals, which may have further limited the availability of macronutrients and micronutrients in soils, was not found.

Laboratory analyses on the amounts of PTEs showed that compared to worldwide background levels and international critical limits the total amounts of Al, Fe, Sr, Cd, Pb and F were very low in the soils of the Kaduna study area. Compared to the areas of endemic skeletal fluorosis, the total concentrations of F and the acid-soluble concentrations of F were too low in the soils of the Kaduna study area to have a detrimental effect on the bone health of the local population.

In the drinking water, neither a significant lack of macronutrients and micronutrients, nor a noticeable oversupply of PTEs was found. The lowest pH and Ca values were detected in the drinking water of the HR study sites, while the LR and NR study sites showed the lowest concentrations of Se and the highest concentrations of F. Compared to the typical mineral composition of the drinking water in northern Nigeria, the pH values and the Ca concentration were low, and the Se and F concentrations were normal in the drinking water of the Kaduna study area. In comparison to guideline levels given by the World Health Organization (WHO), the macronutrient, micronutrient and PTE concentrations in the drinking water were within safe ranges at all the study sites. No significant difference was found between the element concentration in ground and surface water. The concentration of Se in the drinking water of the Kaduna study area was low, but not critically low compared to the Se concentrations in the drinking water of Kashin-Beck-disease areas. The concentrations of F in the drinking water of the Kaduna study area were significantly lower than those found in areas of endemic skeletal fluorosis, meaning that an increased F concentration in the drinking water is not a predisposing factor for the CDR in the Kaduna study area.

The maize in the HR, LR and NR study sites contained normal contents of Mg, K and P, low contents of Ca and Se as well as slightly elevated concentrations of PA compared to West African food composition tables. Comparisons between the mineral contents of traditional and modern maize cultivars showed that the traditional maize cultivars, which were cultivated extensively until the 1960s, contained significantly higher contents of Ca and noticeably lower concentrations of PA than the modern maize cultivars. The shift from the nutrient-rich and PA-poor traditional crop varieties to the nutrient-poor, PA-rich modern crop varieties was therefore assumed to have possibly reduced the nutrient supply, thereby potentially influencing the CDR prevalence rates among the local population.

In comparison to the results from the Kaduna study area, a literature review on the environmental conditions of the CDR areas in Bangladesh, Nigeria, South Africa and The Gambia showed that the bedrock and parent materials were either rich or poor in macronutrients, micronutrients and PTEs. Most of these CDR areas were found to be located in plain areas, where soil types were either rich or poor in soil nutrients. The amounts of macronutrients, micronutrients and PTEs in the drinking water and the food crops of the CDR areas were within safe ranges compared to WHO guideline levels and national food composition tables. In all the CDR areas, including the Kaduna study area, a nutritional change towards a one-sided, micronutrient-poor diet was found, a diet low in meat and milk products and based on the cultivation and consumption of high-yield crop plants.

Conclusions. A direct link between the environmental conditions and the CDR in the Kaduna study area was considered unlikely, as neither a statistically significant lack of macronutrients and micronutrients, nor a statistically significant oversupply of PTEs was found in the environment of this area. Instead, a lack of Ca and Se was found in the locally produced maize varieties. Furthermore, a lack of Ca and elevated contents of PA were found in modern maize varieties compared to traditional maize varieties, which was assumed to be due to differences in the variety and not due to environmental conditions. The change in the food crop varieties was assumed to have promoted a lack of Ca in humans and therefore may have influenced the Ca deficiency in the population of the Kaduna study area.

The environmental conditions of the CDR areas in Bangladesh were greatly different than those of the Kaduna study area, while the environmental conditions of the CDR areas in Gambia, Nigeria and South Africa were to some extent comparable to those of the study area. A general link between environmental conditions and the CDR in developing countries was therefore considered unlikely. However, a change in the choice of the crop plant varieties with a corresponding change in the mineral composition of the nutrition was also found in other CDR areas within developing countries, indicating that it is rather the nutrition than the environmental conditions that impacts the prevalence of CDR.

Future perspectives. To finally be able to exclude the impact of the environment on Ca deficiency and the resulting CDR, further research on the concentrations of macronutrients, micronutrients and PTEs in the ecosystems of CDR areas in developing countries is necessary. Especially, determining their plant-available concentrations should be of interest. Furthermore, future research should include identifying the food crop varieties and analysing their respective macronutrient, micronutrient and PTE contents. In combination with comparative studies on traditional diet and modern diet, the hypothesized impact of a nutritional change on the prevalence of the CDR in developing countries could finally be verified. Especially towards the end of the dry season, food resources become scarce. Collecting data and assessing the birth months of the CDR children should help to identify if a one-sided diet during the dry season is a predisposing factor for the CDR in developing countries. In times of climatic changes and increasing demographic stress, such food scarcities could be especially intense. Further research into these hypotheses could finally support both to deal with the rising numbers of CDR and to raise the awareness and thus improve the food situation in developing countries in general.

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*	Diagnostic soil horizon
-	Not traceable
1.25$(OH)_2$D	Calcitriol (1,25-dihydroxyvitamin D_3)
2	Older soil layer, used in combination with B or C master soil horizons (WRB classification)
25(OH)D	Calcifediol (25-hydroxyvitamin D)
A horizon	Mineral master soil horizon, formed at the surface
AAS	Atomic absorption spectroscopy
AB	Angular blocky soil structure
Ab	Albite plagioclase feldspar mineral ($NaAlSi_3O_8$), feldspar mineral group
Acid-sol.	Acid-soluble
Al	Aluminium
ALP	Alkaline phosphatase
Apt	Apatite phosphate mineral ($Ca_{10}(PO_4)(OH,F,Cl)_2$)
^{back}	Compared to background levels for drinking water quality of a given CDR country or region
BD2	Bulk density of mineral soil between 1.2 and 1.4 kg dm^3
BD3	Bulk density of mineral soil between 1.4 and 1.6 kg dm^3
BD4	Bulk density of mineral soil between 1.6 and 1.8 kg dm^3
BGR	Federal Institute for Geosciences and Natural Resources, Germany
B horizon	Master soil horizon that formed below A horizons, in which all or much of the original bedrock or parent material structure is obliterated
Bit	Biotite phyllosilicate mineral ($K(MgFe)_3(AlSi_3O_{10})(F,OH)_2$), mica mineral group
BS	Base saturation
c	Subordinate soil characteristic, indicating the occurrence of pisolites, combined with A master soil horizons (WRB classification)
Ca	Calcium
CAL	Ca acetate lactate
Ca-Na-Fs	Ca-Na-feldspar (e.g. $(Na,Ca)(Al,Si)AlSi_2O_8$)
CECpot	Potential cation-exchange capacity
Cd	Cadmium
CDR	Calcium-deficiency rickets
Chl	Chlorite ($(Mg,Fe)_3(Si,Al)_4O_{10}$) phyllosilicates mineral group
C horizon	Master soil horizon below A and B horizons, which are little affected by pedogenetic processes

clay	Soil particle sizes < 2 µm
CR	Crumbly soil structure
Cu	Copper
DARDLA	Department of Agriculture, Rural Development and Land Administration of Mpumalanga Provincial Government, South Africa
DIN	German Institute for Standardization (*Deutsches Institut für Normung*)
DW	Dry weight
EDTA	Ethylenediaminetetraacetic acid
ed.	Edition
Ed.	Editor
Eds.	Editors
e.g.	For example (Latin: *exempli gratia*)
F	Fluoride
FAO	Food and Agriculture Organization of the United Nations
FDALR	Federal Department of Agricultural Land Resources, Nigeria
Fe	Iron
Field No.	Field number
Fs	Feldspar tectosilicate mineral ($KAlSi_3O_8$)
g	Subordinate soil characteristic, indicating alternating conditions of oxidation and reduction of sesquioxides, caused by seasonal surface waterlogging (gleyic horizon), combined with A, B and C master soil horizons (WRB classification)
Gbs	Gibbsite hydroxide mineral ($Al(OH)_3$)
Gt	Goethite iron-bearing oxide mineral ($FeO(OH)$)
h	Subordinate soil characteristic, indicating accumulation of organic matter, combined with A master soil horizons (WRB classification)
Hbl	Hornblende double-chain inosilicate mineral (dark amphibole)
HPLC	High-performance liquid chromatography
HR village	CDR-high-risk village in the south-east Kaduna study area, where Ca-deficiency rickets is prevalent in > 5% of all children (Jankassa, Kaso, Koche Koche, Pam Madaki, Telele, Ungwan Bagudu, Ungwan Fada)
HVCF	Hope for the Village Child Foundation, nongovernmental organization near Kaduna City, northern Nigeria
ICP-MS	Inductively coupled plasma mass spectrometry
ICP-OES	Inductively coupled plasma optical emission spectrometry
IITA	International Institute of Tropical Agriculture, Nigeria
Ill	Illite phyllosilicates ($(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$), clay mineral group
ISE	Ion-selective electrode
ISRIC	International Soil Resource Information Centre
ITCZ	Intertropical Convergence Zone
IUSS	International Union of Soil Sciences
K	Potassium
K-Fs	K-feldspar ($KAlSi_3O_8$)

Kln	Kaolinite clay mineral ($Al_2Si_2O_5(OH)_4$)
l	Subordinate soil characteristic, indicating capillary fringe mottling, combined with A, B and C master soil horizons (WRB classification)
Lab No.	Laboratory number
LR village	CDR-low-risk village in the south-east Kaduna study area, where Ca-deficiency rickets is prevalent in ≤ 5% of all children (Kafari, Kujama, Panzato)
LU	Lumpy soil structure
LY	Layered soil structure
MA	Massive soil structure
Ma	Million of years
m AMSL	Meter above mean sea level
Mc	Microcline tectosilicate mineral ($KAlSi_3O_8$), feldspar mineral group
Mca	Mica silicate mineral ($(K,Na,Ca)_2(Al,Mg,Fe)_{4-6}(Si,Al,Fe)_8O_{20}(OH,F)_2$)
Mg	Magnesium
MTSAFRF	Military Topographic Service of Armed Forces of the Russian Federation
n	Number of samples
na	Not available
Na	Sodium
nd	Not determined
NR village	CDR-no-risk village in the south Kaduna study area, where Ca-deficiency rickets is not existing (Dakala)
o	Subordinate soil characteristic, indicating residual accumulation of sesquioxides (pedogenetic), combined with A, B and C master soil horizons (WRB classification)
OC	Organic carbon
P	Phosphorus
p	Subordinate soil characteristic, indicating ploughing, combined with A master soil horizons (WRB classification)
PA	Phytic acid ($C_6H_{18}O_{24}P_6$)
Pb	Lead
PL	Platy soil structure
Pl	Plagioclase tectosilicate mineral ($NaAlSi_3O_8$-$CaAl_2Si_2O_8$)
Plant-avail.	Plant-available
pp.	Pages
ppm	Parts per million
Ps	Pisolites
PTEs	Potentially toxic elements
PTH	Parathyroid hormone
p-value	Probability value, giving the probability of obtaining a test statistic
Qtz	Quartz silicate mineral (SiO_2), mineral group
r	Subordinate soil characteristic, indicating strong reduction, combined with A, B and C master soil horizons (WRB classification)
Ref.	Reference

rhos	Spearman's Rank nonparametric correlation coefficients
s	Subordinate soil characteristic, indicating illuvial accumulation of sesquioxides, combined with B master soil horizons (WRB classification)
sand	Soil particle sizes between 2000 and 63 µm
SB	Subangular blocky soil structure
SD	Standard deviation
Se	Selenium
SG	Single grain soil structure
Si	Silicon
silt	Soil particle sizes between 63 and 2 µm
Sme	Smectite hydrous aluminium phyllosilicate, clay mineral group
Sr	Strontium
t	Subordinate soil characteristic, indicating illuvial accumulation of silicate clay, combined with B and C master soil horizons (WRB classification)
trace	Trace concentrations < 5%
U	Units
UNICEF	United Nations Children's Fund
v	Subordinate soil characteristic, indicating occurrence of plinthite, combined with any master soil horizon (WRB classification)
Vitamin D	Cholecalciferol (vitamin D_3)
Vrm	Vermiculite hydrous silicate, 2:1 clay mineral ($(Mg,Fe,Al)_3(Al,Si)_4O_{10}(OH)_2 4H_2O$)
vs.	Versus
w	Subordinate soil characteristic, indicating development of colour or structure, combined with B master soil horizons (WRB classification)
Water-sol.	Water-soluble
WDXRF	Wavelength dispersive X-ray fluorescence
WHO	World Health Organization
$^{\text{WHO}}$	Compared to the WHO guideline levels for drinking water quality
WRB	World Reference Base for Soil Resources
XRD	X-ray diffractometry
Zn	Zinc
Zrn	Zircon mineral ($ZrSiO_4$), neosilicates mineral group

1 Introduction

1.1 Calcium-deficiency rickets in developing countries

Rickets (Greek: *rachitis* = in or of the spine) is a paediatric disease that is characterized by deformities of the long bones (*genu varum*, *genu valgum* and windswept deformities), a widening of wrists and ankles and a beading of the ribs (rachitic rosary) (Pai, 2011). The disease results from the impaired bone mineralization of the actively growing bone and is therefore found only in children (Dimitri & Bishop, 2007) (see Figure 1.1).

Figure 1.1 Typical clinical signs of CDR in a girl from the rural Kaduna area.
From left to right: deformities of the limbs, including rachitic rosary, the widening of wrists and ankles, windswept deformities and deformities of the upper extremities.
(Photos provided by Dr Christa Kitz)

1 Introduction

Cases of rickets have been found as early as the mid-Holocene (Pfeiffer & Crowder, 2004), but became most prominent in the mid 20th century as English Disease in industrializing England, because of its high prevalence (Fildes, 1986). Due to a natural lack of sunlight in these northern latitudes as well as heavy air pollution, less vitamin D was synthesized from UVB radiation in children's skin. As a consequence, less calcifediol (25(OH)D) was converted in the liver, resulting in less Ca being absorbed from the gut (Wharton & Bishop, 2003). Children affected by this form of vitamin-D-deficiency rickets therefore typically present with low 25(OH)D serum levels (Thacher et al., 2000). After the introduction of clean-air legislation and dietary vitamin D supplementation in most countries of the northern hemisphere, these cases of vitamin-D-deficiency rickets diminished, but have re-emerged again in recent years, particularly in groups with limited exposure to UVB radiation (Prentice, 2013). Amongst others, these are dark-skinned immigrant children in the northern latitudes, infants and toddlers whose parents overuse sunscreen or children who participate too much in indoor activities (Abrahams, 2002; Mughal, 2012; Thacher et al., 2013).

At the same time, a rising number of rickets cases have been reported over the last 30 years from tropical countries, where sunlight is abundant and plasma 25(OH)D levels are within a normal range in the rachitic children (Abrams, 2002). Children affected by this form of Ca-deficiency rickets (CDR), typically present with elevated calcitriol ($1.25(OH)_2D$) serum levels (Bhimma et al., 1995; Fischer et al., 1999), a hormonally active form of vitamin D which is produced in the kidney to increase the release of Ca from bones into blood (Pai, 2011). Especially those children whose diet is one-sided, based on a Ca-poor but phytic acid (PA)-rich nutrition and whose dairy intake is minimal are at high risk for developing CDR (Bereket, 2003; Eyberg & Pettifor, 1986; Fischer et al., 2008). Calculations regarding the daily Ca intake of CDR children show that children consuming such diets receive less than 200 mg of Ca per day, a concentrations that covers only around 25% of the daily required amount in growing toddlers and adolescents (Kitz et al., 2009; National Research Council, 1980; Ross et al., 2011). In the parents generation of the CDR children in tropical countries, rachitic symptoms and osteoporotic fractures are rare (Aspray et al., 2009; Emmert, 2009).

A differential diagnosis of vitamin-D-deficiency rickets and CDR requires information about the clinical picture, X-ray images of the growing bone parts as well as biochemical indicators in the plasma and serum samples. Young children between the ages of 4 and 12 months who present with signs of *craniotabes* and very low 25(OH)D plasma levels are most likely to be affected by vitamin-D-deficiency rickets (Thacher et al., 2000). On the other hand, children between the ages of 15 and 25 months who present with lower limb deformities or a widening of wrists and ankles and who have very high $1.25(OH)_2D$ levels are likely to be affected by CDR (Fischer et al., 2008; Graff et al., 2004). High serum levels of parathyroid hormone (PTH) and low levels of Ca are found in both forms of rickets (Wharton & Bishop, 2003).

To treat rickets, prevention programmes and dietary supplementation with either vitamin D or Ca compounds are recommended (Combs et al., 2008; Graff et al., 2004; Strand et al., 2003). Such programmes are easy to set up, can be run at relatively low cost and are already effective after a few months (see Figure 1.2). However, rickets remains the most common form of metabolic bone disease in children and is on the increase again, especially in developing countries (Dimitri & Bishop, 2007; Wharton & Bishop, 2003).

Checking scientific literature for the prevalence of CDR in developing countries gives the impression that CDR is found only in some areas of the countries Bangladesh (Arnaud et al., 2007; Combs & Hassan, 2005; Combs et al., 2008; Craviari et al., 2008; Fischer et al., 1999), Nigeria (Couppis et al., 2006; Emmert, 2009; Fischer et al., 2000; Graff et al., 2004; Jakob et al., 2010; Keating et al., 2011; Kitz et al., 2009; Oramasionwu et al., 2008; Pfitzner et al., 2001; 1998; Thacher et al., 2009; 2002; 2000; 1999; VanderJagt et al., 2001; Wright et al., 2005), South Africa (Pettifor et al., 1981; 1979; 1978) and The Gambia (Braithwaite et al., 2011; Jones et al., 2009; Prentice, 2013; Prentice et al., 2008; 2006).

Figure 1.2 Bone deformity improvement in a CDR-affected Nigerian girl after 18 months of therapeutic Ca supplementation.
(Photos provided by Dr Christa Kitz)

However, when ones check scientific literature not only for CDR, but for rickets in general, the number of reports found from developing countries greatly increases, indicating that CDR might also be widespread in areas of Benin (Thacher et al., 2006), The Central African Republic (Thacher et al., 2006), Colombia (Sierra et al., 2000), Ethiopia (Belachew et al., 2005; Hojer et al., 1977), Ghana (Arthur et al., 1994; Millot, 1941), Republic of Guinea (Millot, 1941), Kenya (Nyakundi et al., 1994; Oyatsi et al., 1999), Senegal (Thacher et al., 2006), Singapore (Williams, 1946), Sudan (Hag & Karrar, 1995), Tanzania (Msomekela et al., 1999; Muhe et al., 1997) and Uruguay (Hortal et al., 1990) (see Figure 1.3). Cases of rickets have also been reported from some other areas in Nigeria (Agaja, 2001; Akpede et al., 1999; Ekanem et al., 1995; Jelliffe, 1951; Laditan & Adeniyi, 1975; Oginni et al., 2003;

1996; Onyiriuka et al., 2012; Oyemade, 1975; Sharp et al., 1997; Walter et al., 1997).

In most of these studies, no biochemical measurements on 25(OH)D and 1.25(OH)$_2$D were made. Instead, most of the rickets children were, without any differential diagnostic measures, simply diagnosed with vitamin-D-deficiency rickets. The author of this doctoral thesis surmises that this was mostly due to physicians in these countries lacking knowledge on the differential diagnosis of rickets or an advanced laboratory to measure the 25(OH)D and 1.25(OH)$_2$D serum levels of the rickets-affected children.

However, in those few studies where serum 25(OH)D and 1.25(OH)$_2$D levels were analysed, 25(OH)D was almost entirely found to be within a normal range, which is a clear sign for CDR and not vitamin-D-deficiency rickets (Thacher et al., 2006). This suggests that in most developing countries, rickets is not the vitamin-D-deficiency type, but the CDR type (see Figure 1.3). Although further medical analyses and differential diagnoses are still needed in most developing countries to finally prove this hypothesis, already today, even the most conservative estimates indicate that CDR represents a global public health concern (Prentice, 2013).

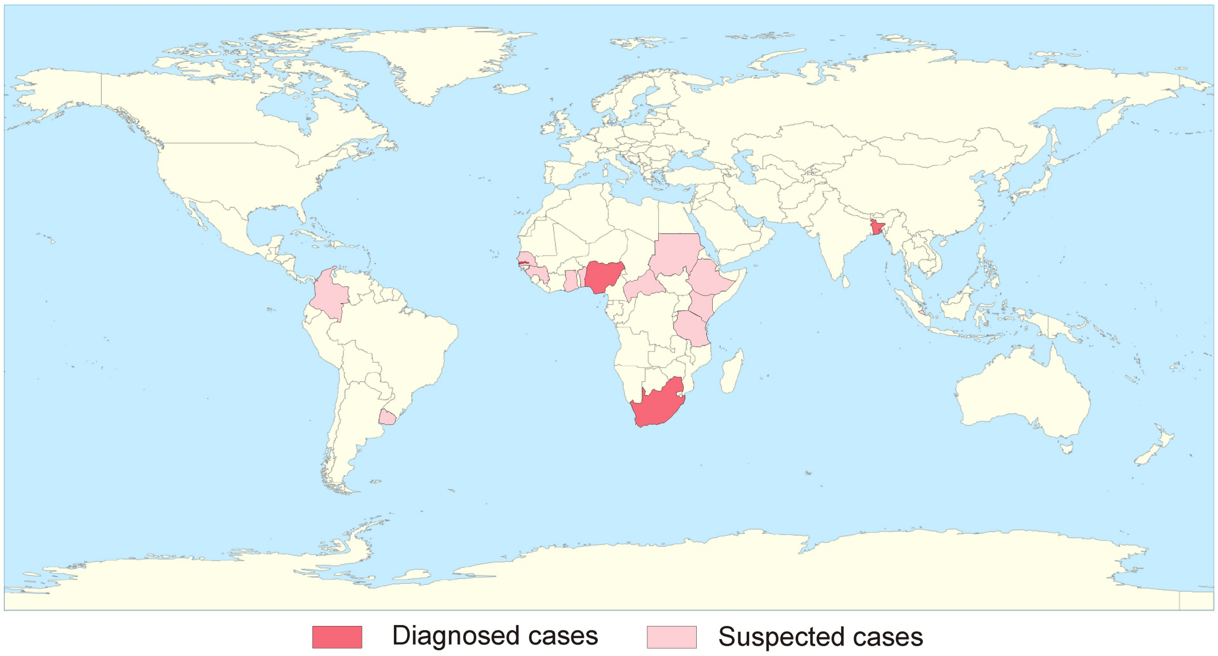

Figure 1.3 Worldwide distribution of diagnosed and suspected cases of the CDR in developing countries.

[World map taken from http://en.wikipedia.org/wiki/File:Worldmap_location_NED_50m.svg; country data on diagnosed cases taken from Arnaud et al. (2007); Braithwaite et al. (2011); Combs & Hassan (2005); Combs et al. (2008); Couppis et al., 2006; Craviari et al. (2008); Emmert, 2009; Fischer et al. (2000; 1999); Graff et al. (2004); Jakob et al. (2010); Jones et al. (2009); Keating et al. (2011); Kitz et al. (2009); Oramasionwu et al. (2008); Pettifor et al. (1981; 1979; 1978); Pfitzner et al. (2001; 1998); Prentice (2013); Prentice et al., (2008; 2006); Thacher et al. (2009; 2002; 2000; 1999); VanderJagt et al. (2001); Wright et al. (2005); country data on suspected cases taken from Arthur et al. (1994); Belachew et al. (2005); Hag & Karrar (1995); Hojer et al. (1977); Hortal et al. (1990); Millot (1941); Msomekela et al. (1999); Muhe et al. (1997); Nyakundi et al. (1994); Oyatsi et al. (1999); Sierra et al. (2000); Thacher et al. (2006); Williams (1946)]

There is scientific consensus that CDR children have a low Ca intake due to a one-sided diet high in cereals but low in meat and dairy products (Combs & Hassan, 2005; Pettifor, 2004). However, such diets are widespread in developing countries in general and are also typical for healthy children in those countries (Fischer et al., 2000). Nowadays, Ca deficiency in CDR children is therefore not considered to be only a consequence of diet. Instead, also genetic disorders (Alhadji, 2011; Thacher, 2003) or poor socio-economic conditions (Okonofua et al., 1991; Combs & Hassan, 2005) are thought to be cofactors of CDR aetiology. Furthermore, some authors have suggested that environmental conditions, such as the depletion of soil nutrients or exposure to the toxic effects of natural, agricultural or industrial environmental contaminants, are predisposing factors for CDR in developing countries (Combs et al., 2008; Prentice, 2013).

While some research has already been conducted on genetic and socio-economic conditions in the CDR areas in developing countries, the number of reports analysing and discussing environmental conditions is relatively small. This is surprising, as most of the elements needed by human bones are obtained via the soil-plant-animal-human pathway (Abrahams, 2002; Combs, 2013; Markert et al., 2000; Steinnes, 2011; 2009; Welch, 2002; Whitehead, 2000), meaning that bone health can easily be impacted by environmental conditions.

1.2 Environmental conditions and bone disease

Bones play key supportive and protective roles in the vertebrate body and are dynamic tissues that are continuously replaced and remodelled. The main mineral component of bones is hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$), which provides the well-known stiffness and load-bearing strength to bones (Pettifor et al., 2003; Skinner, 2013). For healthy bone formation, adequate supplies of essential elements, including macronutrients such as Ca, P and Mg (Combs, 2013; Prentice et al., 2006) as well as micronutrients, such as Cu, Se and Zn (Beattie & Avenell, 1992; Jakob et al., 2010), are needed for crystal and collagen formation, cartilage and bone metabolism, Ca and phosphate homeostasis as well as signalling processes and protection. Furthermore, a number of potentially toxic elements (PTEs), such as Al, Cd, F, Fe, Pb and Sr (Berglund et al., 2000; Järup et al., 1998; Klein, 1990; Noda et al., 1991; Staessen et al., 1999; Svensson et al., 1987), lead to a destabilization of bone strength (Pettifor et al., 2003). Most of these elements are obtained via the soil-plant-animal-human pathway, meaning that bone health can easily be affected by environmental conditions (Abrahams, 2002; Combs, 2013; Markert et al., 2000; Steinnes, 2011; 2009; Welch, 2002; Whitehead, 2000).

Such environment-health interactions are the common subject in the scientific field of medical geology (Davies et al., 2013; Finkelman et al., 2001), a discipline which is also known under the terms geomedicine (Gomes & Silva, 2001; Lag, 1990) or environmental medicine (Fowles et al., 2005). As the medical-geology discipline is relatively young, the number of environmental epidemiological studies is still relatively small (Hough, 2007). However, according to Bunnell et al. (2007), Deckers and Steinnes (2004), Klaasen et al. (2010) and Selinus (2004), the medical-geology discipline is globally emerging.

A classical example of a bone disease that has been associated with environmental conditions is Kashin-Beck disease, a chronic, endemic osteochrondopathy (Fairweather-Tait et al., 2011; Mathieu et al., 2001) (see Figure 1.4, left). The disease is prevalent in northern China, where Se-poor Jurassic siltstone and sandstone are the dominant bedrock. The soils developed on these rocks are rich in organic carbon (OC) and iron oxides, which inhibits the Se uptake by plants (Fordyce, 2013; 2000; Li et al., 2009; Tan et al., 2002; Tan, 1989).

Furthermore, cases of Mseleni joint disease (see Figure 1.4, middle), a form of endemic osteoarthritis, became known from South Africa during the 1980s. The disease is restricted to areas of Quaternary sand deposits, where nutrient deficiencies in soils are assumed to have caused the disease. In fact, analyses of the soil types and their geochemical composition showed the typical soil type to be a nutrient-poor Arenosol, which is acidic, rich in kaolinite clay minerals and low in soil Ca, Mg, K, P, Zn and Cu (Ceruti et al., 2003; Pooley, 1999; 1997).

Besides (micro-)nutrient deficiencies in soils, element toxicities are also considered to be a possible cause of bone diseases. One example of this are the cases of Itai-Itai disease that became known in the 1950s in Japan, where mining operations released high concentrations of Cd and Fe to local soils and drinking-water sources (Cai et al., 1990; Kazantzis, 2004; Noda et al., 1991; Staessen et al., 1999; Wang et al., 1994). Cases of skeletal fluorosis (see Figure 1.4, right) are restricted to areas of acid igneous or mafic parent materials, where environmental F concentrations are well above the WHO guideline levels for drinking water quality (Dodd et al., 1960; Edmunds & Smedley, 2013; Rombo, 2010; Shorter et al., 2010; Teotia et al., 1998).

Figure 1.4 Human bone disease and environmental conditions.
From left to right: Kashin-Beck disease in a Se-deficient area of China, Mseleni joint disease in areas of poor soil fertility of South Africa, skeletal fluorosis in a F-contaminated region of Tanzania.
(Photos provided by Dr Françoise Mathieu, Dr Victor Fredlund and Dr Richard Walker)

Compared to these very clear and scientifically proven findings, studies on the link between rickets and environmental conditions are rare. Although Walker et al. (1996) assumed cases of rickets in Tanzania to be caused by Ca deficiency in drinking water, no environmental studies were done to test this hypothesis. Furthermore, Al toxicity in drinking water from Bangladesh was assumed to be a predisposing factor for bone deformities (Cimma et al., 2004), but Al concentrations were measured only in the serum samples of the CDR-affected children and not in environmental samples. Moreover, Özgür et al. (1996) claimed that a high concentration of Sr in celestine-bearing gypsum (Tekin et al., 2001) was responsible for cases of rickets in the Tertiary Sivas Basin of Turkey, but analyses were only made theoretically on the basis of geological map interpretation.

Only three studies were found in which the mineral and trace element concentrations were measured in both the serum and the environmental samples in the CDR and rickets areas. One study was conducted by a group of scientists associated with Pfitzner et al. (2001), who found the Pb concentrations in the serum of CDR children living in Jos City, Nigeria as well as the Pb concentrations in soil samples taken from the same area to be high.

A second study was published by Liu (2005), who measured the Cu and Zn concentrations in both the serum samples of rachitic camels and the soil samples from their grazing land and found the animals and the soil to be deficient in these elements (see Figure 1.5).

Figure 1.5 Animal bone disease and environmental conditions.
Both pictures show Bactrian camels, living in areas of Cu and Zn impoverished soils in China.
(Photos provided by Dr Zongping Liu)

The third study was made by the author of this doctoral thesis in the context of her Master's thesis (*Diplomarbeit*) (Hartmann, unpublished, 2009) and showed that the soil, drinking water and maize from a CDR area south-east of Kaduna City, northern Nigeria, contained significantly lower Ca concentrations than the soil, drinking water and maize collected from a CDR-unaffected control village nearby (Hartmann & Sponholz, 2012) (see Figure 1.6).

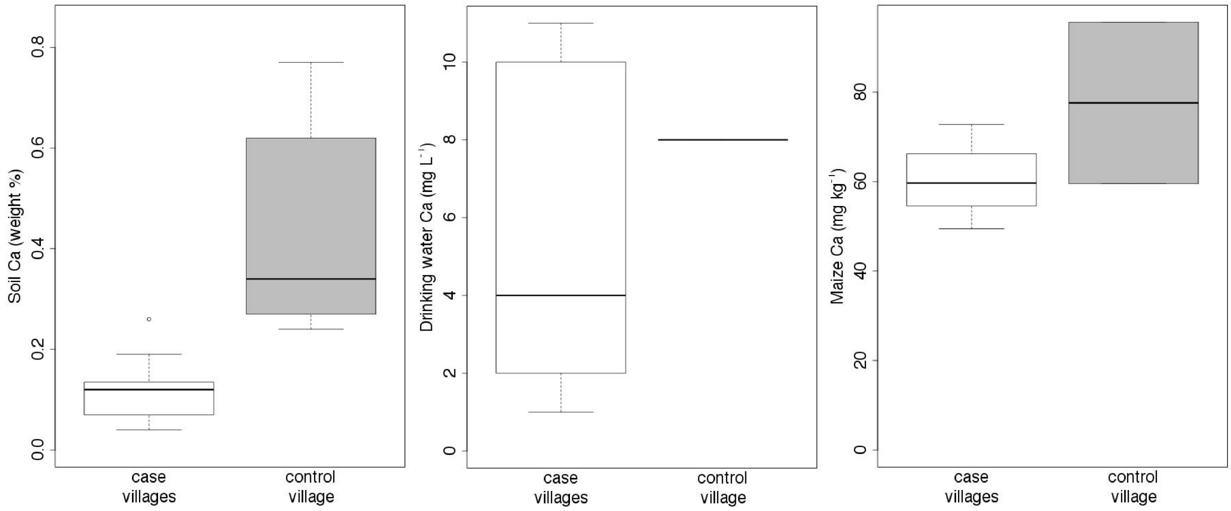

Figure 1.6 Total Ca concentration in the soil, drinking water and maize in CDR case and control villages near Kaduna City, northern Nigeria.

The results of these three studies suggest that environmental conditions may indeed be predisposing factors for the CDR in developing countries. Since most of the CDR areas, as described in Figure 1.3, are located in tropical countries, where soils tend to be poorer and more fragile than soils in temperate regions (Nabhan, 2000a; Plant et al., 1996; Sanchez & Buol, 1975; Weischet, 1980), macronutrient and micronutrient deficiencies may play a key role in causing CDR. In addition, also the risk of environmental pollution is especially high in developing countries where the dispersion of toxic elements due to mining activities is widespread (Davies & Mundalamo, 2010) and where environmental standards and environmental laws are either poor or lacking completely (Agunwamba, 1998; Dissanayake & Chandrajith, 2009). Since many people in developing countries, particularly those who live on subsistence farming, obtain their foods from local sources, element anomalies in the environment may be particularly intense (Abrahams, 2002; Olivier, 1997).

This doctoral work was conducted with the aim of systematically analysing the interactions between the environmental conditions and the CDR in developing countries for the first time. The hypotheses of this research are presented below.

1.3 Hypotheses

1. Environmental conditions are predisposing factors for CDR in a CDR area near Kaduna City, northern Nigeria.

This hypothesis shall be deemed to be highly probable if the:

☐ Bedrock and parent materials are
  - poor in macronutrients and micronutrients
  - rich in PTEs

☐ Land use is characterized by
  - subsistence farming
  - agricultural overuse, resulting in a depletion of macronutrients and micronutrients in soil
  - industrial or agricultural overuse, resulting in high influxes of PTEs in soil

☐ Soil types predominantly have
  - limited agricultural suitability (e.g. Arenosol, Leptosol...)
  - particle sizes unfavourable for plant growth (e.g. predominance of clay, sand...)
  - high contents of low activity clay minerals
  - low concentrations of macronutrients and micronutrients
  - high concentrations of PTEs
  - high complexing potential between certain soil elements

☐ Drinking water shows
  - low concentrations of macronutrients and micronutrients
  - high concentrations of PTEs

☐ Staple food (maize) has
  - low contents of macronutrients and micronutrients
  - high contents of phytic acids (PAs).

2. Environmental conditions are predisposing factors for CDR in developing countries in general.

This hypothesis shall be deemed to be highly probable if the bedrock, the land use, the soil, the drinking water and the foodstuff of the CDR areas in Bangladesh, Nigeria, South African and The Gambia show similar environmental conditions as those found in the Kaduna study area, which is that the ecosystems are demonstrably poor in macronutrients and micronutrients and/or demonstrably enriched in PTEs.

2 Materials and methods

2.1 Study area

To analyse the link between environmental conditions and Ca-deficiency rickets (CDR) in children living in developing countries, a 2500-km² area near Kaduna City, northern Nigeria, was taken as a study area (see Figure 2.1).

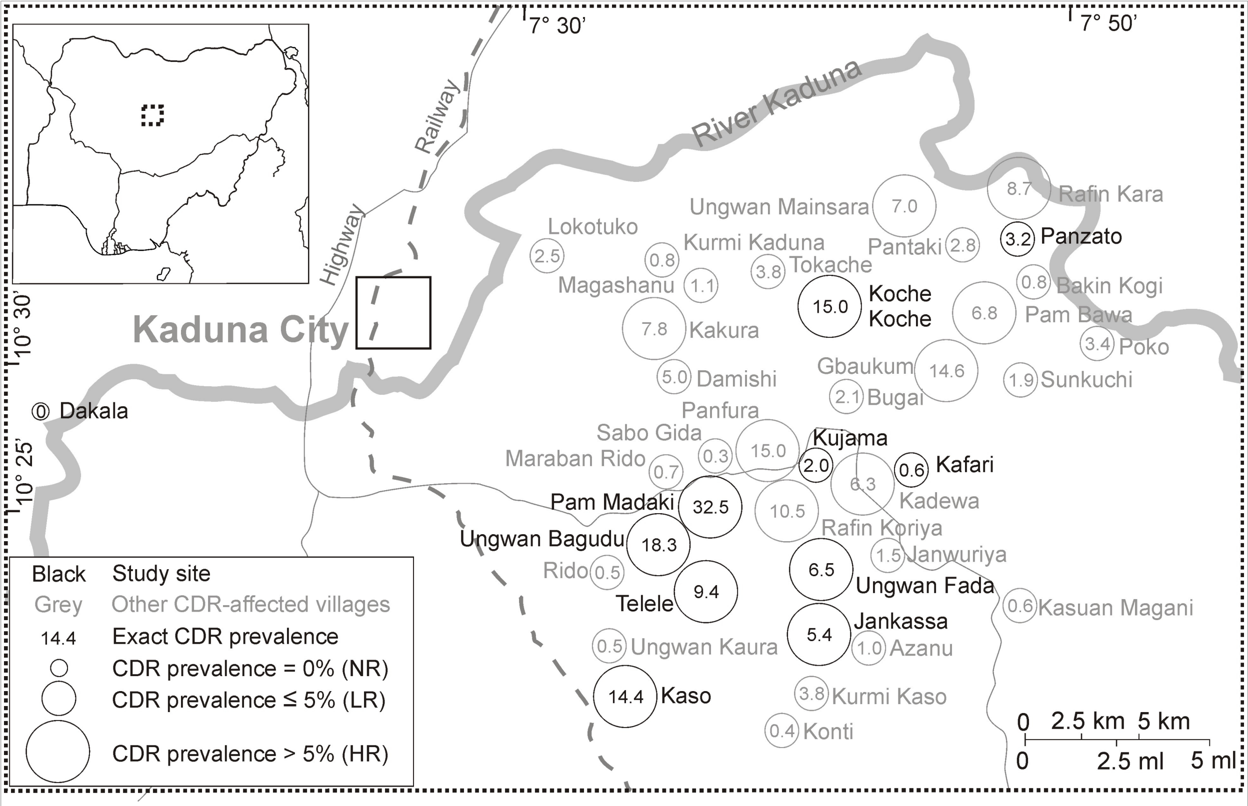

Figure 2.1 Study area, study sites and CDR prevalence rates near Kaduna City.
The map frame is equivalent to the Kaduna study area.
[Geographical information based on MTSAFRF (1985); prevalence data based on Hakuri Matala and Sister Rita Schwarzenberger (personal communication)]

From the central part of this study area (see Figure 2.1), which is located south-east of Kaduna City, a rising number of CDR cases has been reported since the early 2000s by the local nongovernmental organization Hope for the Village Child Foundation (HVCF, 2010). Among the 55000 people living in this 400-km² CDR part of the study area, 150 children were known to be affected by CDR in 2005 (Emmert, 2009), over 700 children were identified in 2008 (HVCF, unpublished 2008) and more than 1000 children in 2011 (HVCF, unpublished, 2011). In 2013, the overall CDR prevalence rate in the CDR part of the study area was estimated to be 5% among toddlers and adolescents aged 15 month to 18 years (Hakuri Matala and Sister Rita Schwarzenberger, personal communication).

Previous epidemiological studies undertaken by doctor of medicine candidate Wulf Emmert (2009) with 53 CDR children (cases) and 48 healthy siblings (controls) in the CDR part of the study area found that the cases show typical clinical symptoms of rickets disease, including deformities of the lower limbs (*genu varum*: 50.0%, *genu valgum*: 19.6%), deformities of the long bones (upper limb: 79.2%, lower leg: 62.3%), widening of wrists and ankles (54.2%) and rachitic rosaries (59.6%). No signs of either dental or skeletal fluorosis were found in the CDR children. Between the cases and controls, no differences were detected in the distribution of sex (cases: 22 boys, 31 girls; controls: 19 boys, 29 girls; p-value = 0.84) or age (case median: 8.0 years, control median: 9.5 years; p-value = 0.28) between cases and controls. The majority of the cases living in the CDR part of the Kaduna study area belonged to the Gbagyi ethnic group (cases: 92.5% Gbagyi, controls: 85.4% Gbagyi). Biochemical analyses showed clear differences between cases and controls, while cases had significantly lower Ca (1.90 vs. 2.19 mmol L^{-1}), significantly lower P (1.47 vs. 1.68 mmol L^{-1}) and significantly lower 25(OH)D (46 vs. 57 nmol L^{-1}) serum levels as well as significantly higher alkaline phosphatase (ALP) (523 vs. 306 U L^{-1}), significantly higher parathyroid hormone (PTH) (24.77 vs. 13.99 pmol L^{-1}) and significantly higher 1.25$(OH)_2$D serum levels (442 vs. 347 pmol L^{-1}) than controls (see Table 2.1). Compared to standard values, the PTH and 1.25$(OH)_2$D levels of the control group were elevated.

Table 2.1 Typical serum levels of CDR case and control children from rural Kaduna area, northern Nigeria.

[Data taken from Emmert (2009)]

Parameter	n	Cases	n	Controls	p-value
		Mean±SD		Mean±SD	
Ca (mmol L^{-1})	52	1.90 ± 0.33	46	2.19 ± 0.16	0.00
P (mmol L^{-1})	52	1.47	46	1.68	0.00
ALP (U L^{-1})	34	523	24	306	0.00
PTH (pmol L^{-1})	53	24.77 ± 12.43	48	13.99 ± 7.57	0.00
25(OH)D (nmol L^{-1})	53	46	48	57	0.00
1.25$(OH)_2$D (pmol L^{-1})	53	442	48	347	0.01

(cases: CDR-affected children; controls: healthy siblings; n: number of samples; U: units)

In addition, the parents of the CDR-affected children, especially the mothers, had elevated PTH and 1.25$(OH)_2$D serum levels. Breastfeeding mothers had again significantly higher levels than non-breastfeeding mothers (Emmert, 2009). Compared to the WHO Child Growth Standards (2006), all the children living in the Kaduna study area were too small for their age (stunted), with cases that were significantly smaller than the controls (case median height: 109.0 cm; control median height: 122.3 cm, p-value = 0.00). None of the children living in the Kaduna study area was undernourished (wasted). Furthermore, no significant difference was found between the cases and controls with regard to weight (case mean weight: 22.1 ± 10.2 kg; control mean weight: 26.0 ± 10.9 kg, p-value = 0.06). According to nutritional interviews, the daily diets of the local population were significantly deficient in Ca. While maize, which is naturally low in Ca, was found to be the staple food all year round, meat, milk products and eggs were eaten only occasionally (Emmert, 2009). The Ca food intake of the children was estimated to be around 200 mg^{-d} (Kitz et al., 2009). A genetic cause for the CDR in the Kaduna study area was considered unlikely, as analyses on 26 family trees (Emmert, 2009), vitamin D receptor polymorphism (FokI, BsmI, ApaI, TaqI and Cdx2) and 24-hydroxylase enzyme promoter regions were negative (Zinßer, unpublished, 2012).

Cases of CDR have also been reported from Kaduna City (Emmert, 2009), but are not part of this doctoral thesis. From rural areas surrounding the CDR part of the study area (see Figure 2.1), no cases of rickets have been reported so far, although this area is likewise densely populated (Sister Rita Schwarzenberger, personal communication). To keep the study-area and study-site map shown in Figure 2.1 as clear as possible, non-CDR villages that were not visited personally were not mapped in Figure 2.1.

To check if environmental conditions predispose children to CDR in the Kaduna study area, a review was conducted of the literature describing the natural environment of this region. Searching the literature revealed that only a few papers or reports published on the environmental conditions of the Kaduna study area could be found. Among those, most detailed information was published in the Land Resource Studies, which were conducted in the 1970s by scientists of the British and Nigerian governments (Bennett et al., 1977a, 1977b; Blair Rains et al., 1977; Wall, 1979). According to these studies, the climate in the study area is affected by the annual shift of the Intertropical Convergence Zone (ITCZ), which results in mean annual precipitation rates of 1300 mm and an average annual temperature of 25.6 °C (Blair Rains et al., 1977). Topographically, the entire area is characterized by gently undulating plains, shallow river valleys and granitoid inselbergs, which rise up sporadically to heights of 200 m above the surface over a monotonous, pediplain-dominated Middle-Belt landscape (Bennett et al., 1977a, Smith, 1981). Precambrian (heavily weathered) granites present the underlying bedrock, covered by Pliocene ferricretes, Quaternary slope deposits and river deposits of various ages (Wall, 1979). Little is known regarding the soil types of the Kaduna Plains, as soil classification work has not yet been made in the rural Kaduna area (Bennett et al., 1977a; Bennett, 1980). According to the evaluation of soil maps derived from large-scale geological maps, Lixisols (WRB classification; Sonneveld, 1996) as well as Lithosols and ferruginous soils (FAO classification; ISRIC, 1964) are the major soil types in the Kaduna area. According to Wall (1979), the soils of the Kaduna area have a moderate to good physical soil fertility and a moderate to low chemical soil fertility. Alkaline and saline soils are absent. The potential natural vegetation of the study area is the savanna trees and grasslands of the northern guinea savanna, which nowadays have mostly been deforested in favour of agricultural use (Blair Rains et al., 1977).

This information was considered insufficient to evaluate the impact of the environment on the CDR in the Kaduna study area. Research trips were therefore evaluated to be necessary to further investigate the physical and chemical characteristics of the natural environment in the Kaduna study area. The visited study sites in the Kaduna study area are presented below.

2.2 Kaduna study sites

To investigate the physical and chemical characteristics of bedrock, soil, drinking water and maize in the Kaduna study area, a research trip of several weeks was undertaken in Nigeria in 2011. Samples of soils and maize were thereby collected at two different study sites by the author of this thesis (see Tables 2.2 and 2.3).

At the end of 2011, however, the security situation in northern Nigeria worsened dramatically and travel warnings of the German Ministry of German Affairs advised cancelling further research trips. Therefore, possibilities of setting up a second study area in another area of Nigeria were explored. Cases of CDR were known from areas around Jos City, northern Nigeria (Fischer et al., 2000; Graff et al., 2004; Keating et al., 2011; Oramasionwu et al., 2008; Pfitzner et al., 2001; 1998; Thacher et al., 2009; 2002; 2000; 1999; VanderJagt et al., 2001; Wright et al., 2005). And in 2013, other CDR cases became known from the rural areas around Kachia and Kwoi City, northern Nigeria (HVCF, unpublished, 2013). However, as both regions were located in the northern part of Nigeria, where conflicts between Christians and Muslims have not stopped even up to now, none of the areas was a feasible possibility.

Table 2.2 Study sites, principal field investigators and types of samples gathered in HR villages in the Kaduna study area.

Study site	CDR prevalence rate	Co-ordinates	Type of sample	Year of investigation	Field No.	Principal field investigator
	(%)					
Pam Madaki	32.5	10°26′N 7°38′E	Drinking water (n = 1)	1996	SR-F96-2	HVCF
Ungwan Bagudu	18.3	10°25′N 7°35′E	Drinking water (n = 1)	2008	P035.1	Lena Hartmann
			Drinking water (n = 1)	2012	SR-F12-1	HVCF
Koche Koche	15.0	10°32′N 7°40′E	Drinking water (n = 1)	2008	KK1709	Verena Ganser
Kaso	14.4	10°21′N 7°34′E	Soil (n = 22)	2011	Cat 1-2 – Cat 2-4	Lena Hartmann
			Soil (n = 9)	2011	Cat 5-1 – Cat 5-4	Marvin Gabriel
			Drinking water (n = 1)	2008	0609K2	Verena Ganser
			Drinking water (n = 3)	2008	P017, P030.1, P030.2	Lena Hartmann
			Maize (n = 3)	2008	Gie4, Gie5, Gie6	Lena Hartmann
Telele	9.4	10°23′N 7°36′E	Bedrock (n = 2)	2008	Telele 1, Telele 2	Lena Hartmann
			Drinking water (n = 1)	1996	SR-F96-1	HVCF
			Drinking water (n = 1)	2008	P067.1	Lena Hartmann
Ungwan Fada	6.5	10°24'N 7°38'E	Drinking water (n = 1)	2008	P138	Lena Hartmann
Jankassa	5.4	10°23′N 7°38′E	Drinking water (n = 2)	2008	P137.1, P137.2	Lena Hartmann
			Maize (n = 3)	2008	WueL2, WueL3, WueL5	Lena Hartmann

(HR villages: CDR prevalence rate > 5%; n: number of samples; Field No.: field number)

Alternatively, an attempt was made to set up a second study area in other developing countries. Cases of CDR have been reported from South Africa (Pettifor et al., 1981; 1979; 1978), The Gambia (Braithwaite et al., 2011; Jones et al., 2009; Prentice, 2013; Prentice et al., 2008; 2006) and Bangladesh (Arnaud et al., 2007; Combs & Hassan, 2005; Combs et al., 2008; Craviari et al., 2008; Fischer et al., 1999). However, personal discussions with scientists from South Africa and The Gambia showed that the cases of CDR have decreased in these two countries during the last few years (Prof. Pettifor, Dr Prentice, Dr Goldberg, personal communication). In Bangladesh, no local partner supporting environmental analyses was available, which would make funding insufficient to run a full research trip over several weeks. In Kenya, where a rising number of rickets cases had been reported in newspapers (Gitonga, 2009; Kageni, 2009; Muraya, 2012), personal discussions with scientists showed that biochemical measurements on 25(OH)D and 1.25$(OH)_2$D levels in rickets-affected children still remained to be done before a diagnosis for either vitamin-D-deficiency rickets or CDR is possible and thus, environmental analyses would be advisable (Prof. Kimiywe, Prof. Bwibo, personal communication).

Table 2.3 Study sites, principal field investigators and types of samples gathered in LR villages in the Kaduna study area.

Study site	CDR prevalence rate	Co-ordinates	Type of sample	Year of investigation	Field No.	Principal field investigator
	(%)					
Panzato	3.2	10°35’N 7°44’E	Soil (n = 31)	2011	Cat 3-1 – Cat 4-4	Lena Hartmann
			Maize (n = 1)	2011	Gie8	Lena Hartmann
Kujama	2.0	10°27'N 7°40'E	Bedrock (n = 1)	2008	Kujama 1	Lena Hartmann
Kafari	0.6	10°27’N 7°41’E	Drinking water (n = 1)	2008	1508KA	Verena Ganser
			Drinking water (n = 1)	2008	P157	Lena Hartmann
			Drinking water (n = 1)	2012	SR-F12-4	HVCF

(Field No.: field number; n: number of samples; LR villages: CDR prevalence rate ≤ 5%)

Table 2.4 Study sites, principal field investigators and types of samples gathered in a NR village in the Kaduna study area.

Study site	CDR prevalence rate	Co-ordinates	Type of sample	Year of investigation	Field No.	Principal field investigator
	(%)					
Dakala	0.0	10°28'N 7°20'E	Bedrock (n = 2)	2008	Dakala 1, Dakala 2	Lena Hartmann
			Maize (n = 2)	2008	WueL1, WueL4	Lena Hartmann
			Drinking water (n = 2)	2008	Dakala 1, Kaduna	Lena Hartmann

(Field No.: field number; n: number of samples; NR village: CDR prevalence rate = 0%)

To still be able to finish this doctoral thesis and to present and discuss research results adequately, samples and previously unpublished data of collaborating scientists and health workers were added to the results of the research trip in 2011. These included drinking water samples (n = 4) taken by HVCF in 1996 and 2012, drinking water samples (n = 3) taken by doctor of medicine candidate Verena Ganser in 2008, soil samples (n = 9) taken by geography graduate student Marvin Gabriel (unpublished, 2012), soil F analysis results from Carmen Breitstadt (unpublished, 2012) as well as the analysis results of bedrock (n = 3), drinking water (n = 11) and maize (n = 8) described by the author of this doctoral thesis in the context of her Master's thesis (*Diplomarbeit*) in 2008 (Hartmann, unpublished, 2009) (see Tables 2.2, 2.3 and 2.4). Most of these samples were taken during pilot studies, were sampled to get a first overview on the environmental conditions of the Kaduna area and were not yet interpreted, discussed or published. Although the number of these samples was relatively small (see Tables 2.2, 2.3 and 2.4), the data were assumed to be still high enough for a first interpretation and assessment.

This approach made it possible to finally present the bedrock (n = 5), soil (n = 62), drinking water (n = 18) and maize (n = 9) data from 11 different study sites in the Kaduna study area. In doing so, the study sites with a CDR prevalence rate greater than 5% were considered CDR-high-risk (HR) villages (n = 7), the study sites with a CDR prevalence rate less or equal 5% were considered CDR-low-risk (LR) villages (n = 3) and the study sites without any cases of CDR were considered CDR-no-risk (NR) villages (n = 1). A prevalence map, including the study area and study sites, is given in Figure 2.1.

2.3 Field methods

2.3.1 Bedrock and parent materials

The structure and mineral composition of the bedrock in the study sites was determined in handpieces, using a 10 x magnifier. All study sites were soil-geographically surveyed for topography and parent material according to the method of Semmel (1993). At three study sites, including one HR village (Telele), one LR village (Kujama) and one NR village (Dakala), five rock samples (n = 5) were taken. At two study sites, including one HR village (Kaso) and one LR village (Panzato), parent materials were described according to the WRB guidelines for soil description (IUSS Working Group WRB, 2006b). The results of the parent-material description are given in Appendix A (see Tables A.1 and A.2).

2.3.2 Land use

The potential natural vegetation of the study sites was determined on the basis of a classification book of Maydell (1990). Furthermore, to become familiar with the land-use techniques, crops and fertilizers used as well as the intensity of the industrial use in the Kaduna study area, informal interviews were conducted with local farmers at all study sites. The interview results are presented in Appendix A (see Tables A.3 and A.4).

2.3.3 Soils

Two of the most landscape-representative study sites, including the HR village Kaso and the LR village Panzato, were analysed quantitatively for soil parameters. Soil profiles (n = 18) were dug along toposequences (n = 5). Soils were described and classified according to the WRB classification system (IUSS Working Group WRB, 2006a; 2006b). For each soil horizon, the soil colour was determined in a moist condition according to Munsell (2000). Bulk soil samples (n = 55) were taken from each soil horizon and 200-g soil samples were stored in polyethylene bags for a duration of 2 months. Details on the results of the soil description and soil classification are given in Appendix A (see Tables A.5, A.6, A.7 and A.8).

2.3.4 Drinking water

The drinking-water samples taken by the author of this thesis (n = 11) were collected from surface water (river) and groundwater (borehole, well) sources at 7 study sites, including 5 HR villages (Jankassa, Kaso, Telele, Ungwan Bagudu and Ungwan Fada), one LR village (Kafari) and one NR village (Dakala). All samples were measured for pH with Merck indicator strips. Afterwards, the water samples were acidified to a pH of 3.5 and stored unfrozen in pre-cleaned 100-ml polyethylene bottles for a duration of 2 months before laboratory analyses were started. The drinking water samples taken by Verena Ganser (n = 3) were collected from groundwater (well) sources at two HR villages (Kaso and Koche Koche) and one LR village (Kafari). The samples were stored frozen in pre-cleaned polyethylene bottles for a duration of 6 months before laboratory work was started. The drinking water samples taken by HVCF (n = 4) were collected from surface water (river) and groundwater (borehole, well) sources in 3 HR villages (Pam Madaki, Telele and Ungwan Bagudu) and one LR village (Kafari). The sampling methods and consistency of storage bottles are unknown. All the samples were stored unfrozen for a duration of approximately 3 months before laboratory work was started.

2.3.5 Maize

The analyses on food crops were restricted to maize, as it was identified to be the staple food in the Kaduna study area. Fire-dried maize cobs (n = 9) were collected among farmers from four study sites, including two HR villages (Jankassa and Kaso), one LR village (Panzato) and one NR village (Dakala). The samples were stored unfrozen in 500-g polyethylene bags for a duration of 4 months before laboratory work was started.

2.4 Laboratory analyses

2.4.1 Bedrock

From two rock samples (n = 2), sampled at one HR village (Telele), thin sections were prepared by cutting thin layers of the samples, gluing them on object slides of 26 mm x 48 mm and grinding the slides to a thickness of 25 µm (Deperieux Rehwald). Thin-section analyses were performed on a polarization microscope (Leica Microsystems) at the *Geologisches Institut*, *Julius-Maximilians-Universität Würzburg*, Germany. In addition, the rock samples were analysed by wavelength dispersive X-ray fluorescence (WDXRF) (Phillips PW 1480) (Govindaraju, 1994) to obtain their geochemical fingerprints. Therefore, the samples were crushed to particle sizes of less than 40 µm (with a tungsten-carbide vibration disc mill) and melted down at 1100 °C onto Spectromelt ammonium-nitrate glass fusion discs (Burhke et al., 1998). All the rock analyses were conducted at the *Institut für Geodynamik und Geomaterialforschung*, *Julius-Maximilians-Universität Würzburg*, Germany.

2.4.2 Soils

The soil samples were dried at 40 °C for 12 hours, disaggregated and sieved through a 2-mm nylon sieve mesh. Analyses on the texture (pipette and sieving) were made according to Reeuwijk (2002) at the *Bodenphysik Labor*, *Johann Wolfgang Goethe-Universität Frankfurt*, Germany. For the analyses on clay mineralogy, soil samples were separated for clay. Then, 50 mg of each dried clay sample was re-suspended in 2 ml of deionized water.

From each sample, 1 ml suspension was pipetted onto 3-cm² glass plates and dried over night at room temperature. The redried clay preparations were then measured with copper tubes by X-ray diffractometry (XRD) (PANalytical X'Pert Pro). The mineralogical composition was estimated semiquantitatively (Hardy & Tucker, 1988). Analyses on clay mineralogy were made at the *Sediment Labor*, *Johann Wolfgang Goethe-Universität Frankfurt*, Germany. The soil pH values were measured in 0.1-M KCl solution by electrometric measurement with a WTW E 56 combination electrode (Meiwes et al., 1984). The OC was determined by wet combustion, adding potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4) to the soil samples before measuring with a spectral photometer (Milton Roy C21) (DIN EN 19684, 1977a). The plant-available concentrations of P were measured by spectral photometer (Milton Roy C21) after adding Ca acetate lactate (CAL) and ammonium (NH_4) molybdate as a colouring agent. CAL was also used to determine the plant-available K concentration, while the eluate was measured by atomic absorption spectroscopy (AAS) (Perkin Elmer Analyst 300) (Schüller, 1979). The plant-available concentrations of Mg and Ca as well as the potential cation-exchange capacity (CECpot) and base saturation (BS) were determined by adding buffered (pH 8.1) barium chloride ($BaCl_2$) solution to the soil samples. The macronutrient concentrations were then measured by AAS (Perkin Elmer Analyst 300) (DIN EN 19684, 1977b). The analyses were conducted at the *Bodenchemie Labor*, *Johann Wolfgang Goethe-Universität Frankfurt*, Germany. The water-soluble concentrations of Se were measured by inductively coupled plasma mass spectrometry (ICP-MS) after shaking 1.25 g of milled soil (particle size < 70 µm) with 12.5 ml of deionized water for 15 min, centrifuging at 2500 rpm for 10 min, removing supernatant and adjusting to 1% HNO_3 and 0.5% HCl (Watts et al., 2010). The water-soluble Se was measured at the British Geological Survey, Keyworth, United Kingdom. The total concentrations of Al, Fe, Cd, Cu, Pb, Se, Sr and Zn were extracted with aqua regia and measured by AAS (Perkin Elmer Analyst 300) (DIN EN 13346, 2001). The analyses were performed at the *Bodenchemie Labor*, *Johann Wolfgang Goethe-Universität Frankfurt*, Germany. For the determination of the total F concentrations, the soil samples were first incinerated overnight at 550°C and were then mixed with a sodium hydroxide solution (NaOH), deionized water (H_2O) and hydrogen chloride (HCl). The F concentrations were measured with an ion-selective electrode (ISE) (Metrohm 867) (DIN EN 38405, 1985). The acid-soluble concentrations of F were extracted by adding 1 M of hydrochloric acid (HCl), sodium citrate ($C_6H_5Na_3O_7$), sodium acetate (CH_3COONa) and deionized water (H_2O) and were subsequently measured by ISE (Metrohm 867) (DIN EN 16279, 2012). All the F-analyses were carried out at the *Landwirtschaftliche Untersuchungs- und Forschungsanstalt Nord-West*, Hameln, Germany.

Due to a lack of sampling material and limited financial resources, analyses on clay minerals, micronutrients and potentially toxic elements (PTEs) were made only on the most representative samples. For some samples, laboratory experiments failed for unknown reasons. For all the samples where data were missing due to one of these reasons, the respective table cells were marked with nd (not determined). Details on the results of the soil laboratory work are provided in Appendix B (see Table B1 to Table B14).

2.4.3 Drinking water

The Ca concentrations in the drinking water were measured colorimetrically with Merck rapid tests (116125 Aquamerck) at the *Institut für Geographie und Geologie*, *Julius-Maximilians-Universität Würzburg*, Germany. For Se analyses, the drinking water samples were filtered with a 0.45-µm membrane and then acidified with 1.0 Vol% of concentrated nitric acid (HNO_3) and measured by inductively coupled plasma optical emission spectrometry (ICP-OES) (Perkin Elmer 5000A) (DIN EN 38406, 1999). The analyses on drinking water samples were carried out at the *Bundesanstalt für Geowissenschaften und Rohstoffe*, *Hannover,* Germany. The F concentrations in the drinking water taken from surface water (river) sources were dyed with alizarin ($C_{14}H_8O_4$) and zirconyl chloride ($ZrOCl_2*8H_2O$) and measured by spectrophotometer (Thermo Scientific Spectronic 20D) at Kaduna State Water Board Chemistry Laboratory (KDSWB), Kaduna City, northern Nigeria. The F concentrations in the drinking water taken from groundwater (borehole and well) sources were measured by ion chromatography (Thermo Scientific Dionex) at the Environmental Measurements Laboratory, University of California, Berkeley, United States.

Due to a lack of sampling material and limited financial resources, analyses on F and Se were made only on the most representative samples. For all the samples where data were missing due to one of these reasons, the respective table cells were marked with nd. Details regarding the results of the drinking water laboratory work are given in Appendix C (see Table C.1).

2.4.4 Maize

The maize samples were incinerated overnight in a muffle furnace at 520 °C. For measurements on the Ca, Mg and K contents, the maize ash of each sample was dissolved in 5 M of HNO_3 and measured by AAS (Varian SpectrAA 220FS). The concentrations of P in maize ash were determined photometrically by using molybdate-vanadate reagents (yellow-method) (Steffens, 2004). All these analyses were performed at the *Institut für Pflanzenernährung*, *Justus-Liebig Universität Gießen*, Germany and the *Julius-von-Sachs-Institut für Biowissenschaften*, *Julius-Maximilians-Universität Würzburg*, Germany. The contents of Se in maize were measured by AAS (Perkin Elmer 2380) after drying, milling, sieving and dispersing in 25% hydrochloric acid (HCl) solution by ultrasonic bath (DIN EN 38405, 1994). The results are given in dry weight (DW). To measure the phytic acid (PA) contents in maize, maize kernels were dried, milled and sieved for particle sizes of less than 1 mm. The sieved samples were extracted with 20 ml of 2.4% HCl solution (3 h, 22 °C). From the extracted solution, 1 ml was diluted by 40 ml of H_2O. The PA was prepurified according to a modification of the technique of Skoglund et al. (1997), using Dowex AG 1 x 4, mesh 100-200 (Cl^- form 0.5 g), 25 ml of H_2O and 0.025 M^{-L} of HCl as eluents. The PA was separated on 5-cm columns (Mono-Q Short) and were measured with an inert high-performance liquid chromatography (HPLC) system (Gradient pump 2249 and Low Pressure Mixer, Pharmacia) at an absorption of 290 nm (UV-Vis detector VWM 2141, Pharmacia). The peaks were identified by using PA standards. The chromatograms were evaluated by the PC Integration Pack software (Kontron-Biotek, Neufahrn, Germany) (Schlemmer, 2010; Schlemmer et al., 2001). The PA contents in maize were determined at the *Max Rubner-Institut, Karlsruhe*, Germany. The results are given in DW.

Due to a lack of sampling material and limited financial resources, analyses on Se and PA were made only on the most representative samples. For some samples, laboratory experiments failed for unknown reasons. For all the samples where the data were missing due to one of these reasons, the respective table cells were marked with nd. Details on the results of the maize laboratory work are given in Appendix D (see Tables D.1 and D.2).

2.5 Statistical analyses

To better show the differences in the concentrations of macronutrients, micronutrients as well as PTEs with increasing soil depth and between the HR, LR and NR villages, the mean standard deviation (SD) and median concentrations were calculated with Microsoft Excel for all soils and soil horizons as well as for drinking water and maize samples. The results of these calculations are presented in the Chapters 3.4, 3.5 and 3.6 of this thesis.

A soil quality assessment was performed by comparing the concentrations of macronutrients, micronutrients and PTEs in the Kaduna study area soils to Nigerian, West African and world background levels as well as critical limits. Whenever possible, the results of this study were also compared to the macronutrient, micronutrient and PTE concentrations in areas of endemic bone diseases, such as Kashin-Beck disease, Mseleni joint disease or skeletal fluorosis. To make the main results easier to understand, box plot diagrams were generated using the free software programming language R. The box plots included the median, upper and lower quartile, minimum and maximum values and outliers of the data presented in this study.

To be able to identify any significant element interdependencies and the complexing potential of soil texture, pH, OC, CEC, BS, macronutrients, micronutrients as well as PTE concentrations, Spearman's Rank nonparametric correlation coefficients (rhos) were calculated with Microsoft Excel. Negative rhos show a negative correlation between certain soil parameters, positive rhos show a positive relation and complexing potential between certain soil parameters. Those rhos that were greater than 0.55 were interpreted to be statistically significant. The results of the Spearman's Rank correlation analyses are given and discussed in Chapter 3.4.10.

2.6 Literature review

For reasons of completeness, a literature review was done on the environmental conditions of other CDR areas within developing countries. In doing so, only countries and areas where clear differential diagnoses were made in favour of CDR were taken.

Table 2.5 CDR areas within developing countries, other than the Kaduna study area.

[Based on (1) Fischer et al. (2000); (2) Karim et al. (2003); (3) HVCF (unpublished, 2013); (4) Thacher et al. (2000); (5) Pettifor et al. (1979); (6) Jones et al. (2009)]

Country	District/ Local Government	Village names	CDR prevalence rate	Ref.
			(%)	
Bangladesh	Chittagong	Chakaria, Cox's Bazaar Sadar, Kutubdia, Moheskhali, Ramu, Teknaf, Ukhia	8.7	(1)
	Jessore	Jessore City	na	(2)
	Sylhet	Sylhet City, Sunamganj	na	(2)
Nigeria	Kwoi, Kachia	Ankung, Bitaru, Chori, Daddu, Fai, Forgye, Gidan Gyara, Gidan Mana, Gidan Tagwai, Kurmin Jatau, Kurmin Musa Kwaturu, Nok, Sabon Sarki, Sab-Zuru, Sanbang and Ungwan Rana	na	(3)
	Jos	Jos City	9.0	(4)
South Africa	Gert Sibande	Driefontein, Piet Retief	na	(5)
The Gambia	Kiang West	Keneba	< 0.6	(6)

(Ref.: reference; na: not available)

These areas included the Chittagong, Jessore and Sylhet districts in Bangladesh (Arnaud et al., 2007; Combs & Hassan, 2005; Combs et al., 2008; Craviari et al., 2008; Fischer et al., 1999), the Kwoi Local Government area and the Kachia Local Government area in Nigeria (HVCF, unpublished, 2013), the Jos Local Government area in Nigeria (Fischer et al., 2000; Graff et al., 2004; Keating et al., 2011; Oramasionwu et al., 2008; Pfitzner et al., 2001; 1998; Thacher et al., 2009; 2002; 2000; 1999; VanderJagt et al., 2001; Wright et al., 2005), the Gert Sibande District (Mpumalanga Province) in South Africa (Pettifor et al., 1981; 1979; 1978) and the Kiang West District in The Gambia (Braithwaite et al., 2011; Jones et al., 2009; Prentice, 2013; Prentice et al., 2008; 2006). In the Chittagong District, the Jos Local Government area and the Kiang West District, CDR prevalence rates were 8.7% (Kabir, 1998; Kabir et al., 2004), 9.0% (Pfitzner et al., 1998) and less than 0.6% (Jones et al., 2009), respectively (see Table 2.5). In the Gert Sibande District, approximately 13% of the paediatric population had hypocalcaemia (Pettifor et al., 1981). For the other districts and areas, no prevalence statistics were available.

The literature review was based on land resource studies of the respective countries as well as papers published in international scientific journals.

3 Results and discussion

3.1 Underlying bedrock

Three different bedrock types were identified in the Kaduna study area. These included Older Granites, consisting of porphyric granites (Ephraim, 2012; Kröner et al., 2011; Obiora, 2012), migmatite-gneiss complex comprised of migmatitic gneisses (Obaje, 2009) and metasediments, which were typically composed of semipelitic biotite-muscovite schists (Caen-Vachette & Ekwueme, 1988) (see Figure 3.1). All the rock types belong to the Precambrian crystalline basement (Ferré et al., 1996; Odeyemi, 1980; Rahaman & Malomo, 1983; Rahaman & Ocan, 1978), which constitutes approximately 40% of Nigeria's geology (Schlüter, 2006).

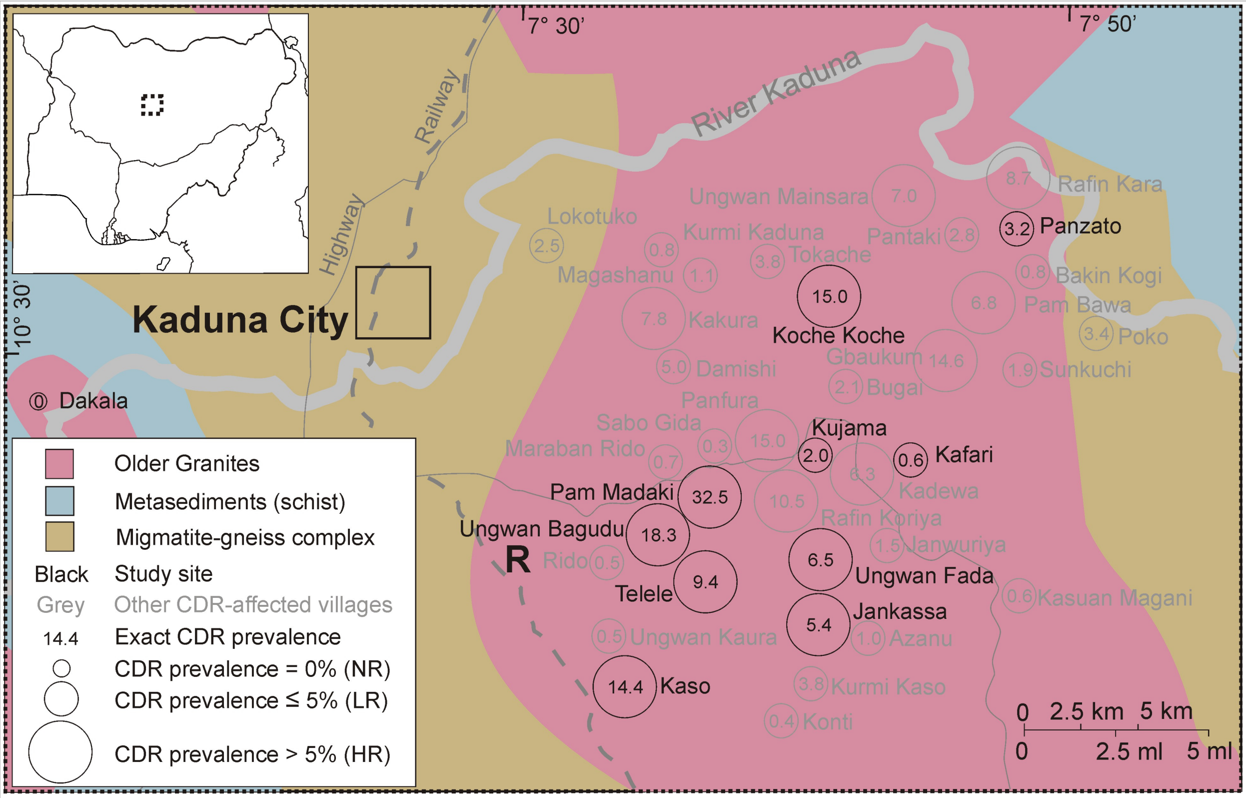

Figure 3.1 Modified geological map of the Kaduna study area.
The map frame is equivalent to the study area, a black bold R shows the location of an oil refinery. [Geological information based on a 1:400000 geological map (Kaduna State Geological Survey, 2008) and the rock determination work of this study; geographical information based on MTSAFRF (1985); prevalence data based on Hakuri Matala and Sister Rita Schwarzenberger (personal communication)]

Due to the old ages and the consistent tropical climate conditions, the bedrock in the Kaduna study area has been deeply chemically weathered to saprolite (Trescases, 1992), a condition that becomes visible under deep drilling and well-construction activities.

Based on the evaluation of geological maps (Kaduna State Geological Survey, 2008; Oyo, 1996), Older Granites were identified to be the dominant bedrock in the CDR part of the study area, while in the western and eastern parts of the study area, rocks from the migmatite-gneiss complex and metasediments were indicated in the maps. The rock determination work of this study, however, revealed the area around the CDR-no-risk (NR) village Dakala to be underlain by Older Granites and not by rocks of the migmatite-gneiss complex or metasediments. Such close paragenesis of different rock types is typical for the Nigerian basement complex (Alabi, 2011; Fagbami, 1981). The geological map, as shown in Figure 3.1, was modified accordingly.

That the underlying bedrock around the NR village Dakala is composed rather of Older Granites than the rock types of the migmatite-gneiss complex or the metasediments was also confirmed by wavelength dispersive X-ray fluorescence (WDXRF) analyses. A comparison between the Older Granites in CDR-high-risk (HR) villages and the Older Granites in the NR village Dakala clearly showed a similar chemical composition, with SiO_2, K_2O and Na_2O as the main components of the Older Granites in both villages (see Table 3.1). In contrast to the rocks of the migmatite-gneiss complex and metasediments, Older Granites typically contain higher contents of SiO_2 and K_2O, but lower contents of CaO and MgO (Annor et al., 1997; Kröner et al., 2001; Tijani et al., 2006) (see Table 3.2).

Table 3.1 Chemical composition of granites in the Kaduna study area.
[Based on Hartmann (unpublished, 2009)]

Study site	Lab No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_3
		(mass%)									
HR village	Dg	74.0	0.1	14.0	1.4	0.0	0.2	0.9	3.6	4.9	0.1
	Dp	73.3	0.2	14.6	1.7	0.0	0.2	0.9	3.6	5.1	0.0
LR village	P133.1	75.3	0.4	12.6	2.5	0.0	0.6	1.1	2.7	3.9	0.1
NR village	P160	74.5	0.1	13.0	1.6	0.0	0.2	0.8	2.2	6.3	0.1

(Lab No.: laboratory number; HR village (Telele): CDR prevalence rate > 5%; LR village (Kujama): CDR prevalence rate ≤ 5%; NR village (Dakala): CDR prevalence rate = 0%)

Compared to the typical geochemical composition of Nigerian Older Granites (Egbuniwe et al., 1985), the Older Granites in the Kaduna study area are relatively low in Ca. Furthermore, the Older Granites are also low in Ca when compared to the concentrations in granite from world geochemical background studies (Blatt & Tracy, 1996). The Ca concentrations were therefore assumed to be low in the ecosystems of the Kaduna study area in comparison to the Ca concentrations in other granite areas worldwide (see Tables 3.1 and 3.2).

A comparison of the average geochemistry of granites to that of other rock types, such as limestone, basalt, quartzite or sandstone, shows significant differences with respect to macronutrient concentrations. While areas underlain by limestones or basalts are known to be generally rich in macronutrients, such as Ca or Mg (Blatt & Tracy, 1996; Pettijohn, 1975), areas underlain by quartzite and sandstone are typically poor in most macronutrients (Blatt et al., 1972; Blatt & Tracy, 1996). According to Garrett (2013), the latter rock types therefore pose much higher risks of causing macronutrient deficiencies in ecosystems than granites do (see Table 3.2). A severe macronutrient deficiency in the ecosystems of the granite-dominated CDR-high-risk villages is therefore unlikely.

Table 3.2 Background major element composition of common rocks in Nigeria and worldwide.

[Based on (1) Egbuniwe et al. (1985); (2) Kröner et al. (2001); (3) Annor et al. (1997); (4) Blatt & Tracy (1996); (5) Blatt et al. (1972); (6) Pettijohn (1975)]

Parent material	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_3	Ref.
	(mass%)										
Older Granites (Nigeria)	70.4	0.5	15.0	1.5	0.0	0.3	1.9	5.2	3.8	0.1	(1)
Migmatite-gneiss complex (Nigeria)	66.3	0.6	15.9	2.0	0.1	1.3	3.4	5.2	1.6	0.2	(2)
Metasediments (schist) (Nigeria)	62.7	1.1	16.7	1.1	0.1	2.0	2.5	2.8	2.8	0.1	(3)
Granites (world)	72.0	0.3	14.4	1.2	0.1	0.7	1.8	3.7	4.2	0.1	(4)
Basalt (world)	50.1	1.9	15.9	3.9	0.2	7.0	9.7	2.9	1.1	0.3	(4)
Quartzite (world)	95.4	na	1.1	0.4	na	0.1	1.5	0.1	0.2	na	(4)
Sandstone (world)	77.6	na	7.1	1.7	na	1.2	3.1	1.2	1.3	na	(5)
Limestone (world)	5.2	> 0.1	0.8	0.5	na	7.9	42.6	0.1	0.3	> 0.1	(6)

(Ref.: reference; na: not available)

Thin-section analyses of Older Granites in the HR village Telele showed the Older Granites to be composed of quartz (SiO_2), K-feldspars ($KAlSi_2O_8$), plagioclase ($NaAlSi_3O_8$-$CaAl_2Si_2O_8$) and biotite ($K(MgFe)_3(AlSi_3O_{10})(F,OH)_2$) (see Figure 3.2). These minerals are estimated to be present in concentrations of 30%, 15%, 20% and 15%, respectively (see Table 3.3). No evidence was found for any rock minerals containing Zn, such as zincite, willemite or hemimophite. Biotite, plagioclase and feldspars are host minerals for Cu, Cd, P, Pb, Se and Sr, respectively (Kabata-Pendias & Mukherjee, 2007; Reimann & Caritat, 1998), meaning that slightly elevated concentrations of these elements may be expected in the environment of the Kaduna study area. Furthermore, biotite contains verifiable concentrations of F, an element that is known to potentially affect human dental and skeletal health if elevated in the environment (Edmunds & Smedley, 2013; Smedley et al., 1995).

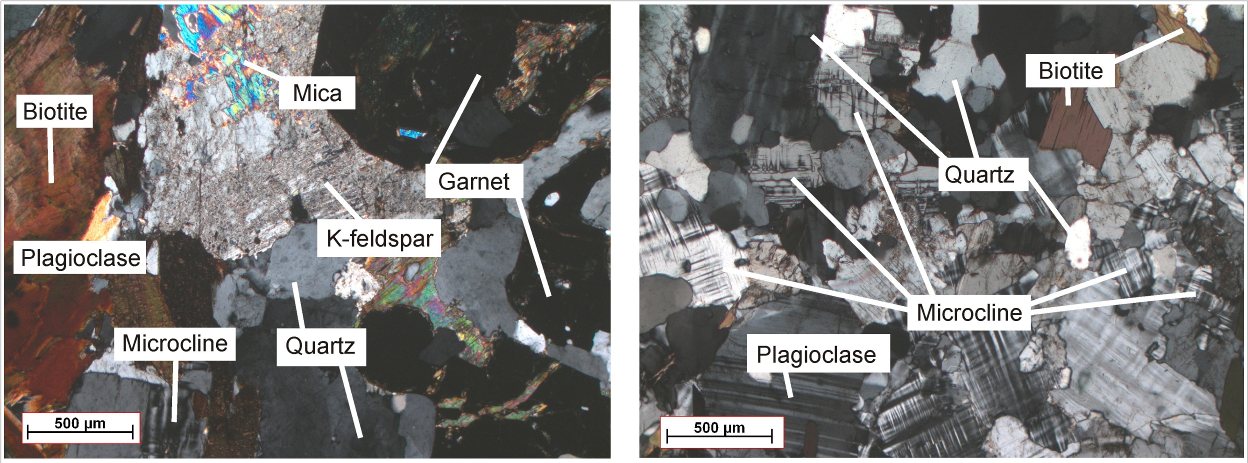

Figure 3.2 Thin sections of Older Granites in the HR village Telele.
Laboratory number of left sample: Dg; laboratory number of right sample: Dp;
HR village: CDR prevalence rate > 5%
[Photos taken from Hartmann (unpublished, 2009)]

In such a way, a high prevalence of dental fluorosis in children was found in the Choma

District of the southern province of Zambia and was linked to porphyric granites, containing up to 10% biotite (Shitumbanuma et al., 2007). Concentrations of F are also known to be high in the Mayo Tsanaga River Basin, in the Far North Region, Cameroon, for instance, where Biu Plateau granites contain high concentrations of biotite (Fantong et al., 2010) (see Table 3.3).

Table 3.3 Background mineral composition of bedrock in the CDR Kaduna study area and in areas of endemic fluorosis in Africa.

[Based on (1) Hartmann (unpublished, 2009); (2) Shitumbanuma et al. (2007); (3) Fantong et al. (2010)]

Study area	**Bedrock**	**Qtz**	**K-Fs**	**Pl**	**Bit**	**Hbl**	**Mc**	**Zrn**	**Apt**	**Ref.**
		(%)								
CDR area near Kaduna City, Nigeria	Older Granites	30	15	20	15	-	-	trace	-	(1)
Fluorosis area in Zambia	Choma-Kaloma batholith	25	-	10	10	trace	50	-	trace	(2)
Fluorosis area in northern Cameroon	Biu Plateau Granite	20	38	27	10	-	-	-	trace	(3)

(Apt: apatite; Bit: biotite; Fs: feldspar; Hbl: hornblende; Mc: microcline; Pl: plagioclase; Qtz: quartz; Zrn: zircon; Ref.: reference; -: not traceable; trace: trace concentrations < 5%; CDR: Ca-deficiency rickets)

The relatively high concentrations of biotite in the granites of the study area therefore implies that the F concentration is also elevated in the ecosystems of the Kaduna study area, which may have further effects on the bone health of the local population. However, as the bedrock of the Kaduna study area was found to be covered again by different deposits, which were the actual parent materials of the Holocene soil formation (Heinrich, 1995) and the main mineral sources of food crops, the environmental conditions were not purely reflected by the underlying bedrock, but were also a function of the geochemical conditions of the overlying parent materials (see Chapter 3.2).

In summary, three main rock types are found in the Kaduna study area, including Older Granites, migmatite-gneiss complex and metasediments. Among these, the Older Granites were the dominant bedrock in both the CDR and non-CDR villages. Geochemical analyses showed the Older Granites to contain relatively low concentrations of Ca compared to Nigerian Older-Granite background levels and background levels of granites worldwide. Areas of severe macronutrient deficiency, however, are rather associated with quartzite or sandstone than granite. Thin-section analyses showed that the Older Granites in the Kaduna study area contained relatively high contents of biotite, which is a typical host mineral for F. As elevated concentrations of F are typically associated with high prevalence rates of fluorosis, raised F concentrations in the study area's ecosystems were thought to may also have a certain influence on the bone health of the local population in the Kaduna area. However, as the overlying parent materials rather than the underlying bedrock have the main influence on the soil and plant geochemistry in the Kaduna study area, such element anomalies may be weakened in the soil-plant pathway.

3.2 Overlying parent materials

3.2.1 Types

Three different types of overlying parent materials were distinguished in the Kaduna study area: slope deposits, river deposits and aeolian deposits. Slope deposits were understood as (allochthonous) materials derived from upslopes through erosion processes (Daniels & Hammer, 1992; Eswaran et al., 1990). Loose, unconsolidated sediments which have been transported by water and have redeposited in layered structures in some positions were interpreted as river deposits. High contents of silty material in soils were assumed to have derived from harmattan dust and were considered to be aeolian deposits.

3.2.1.1 Grus slope deposits

On the foot slopes of the inselbergs, which had slope gradients of up to 4° and mean heights of 670 m above mean sea level (m AMSL), the slope deposits contained high contents of angular, coarse-grained granitoid grus and were physicochemically comparable to the underlying granitoid bedrock (Isichei et al., 1990). The grus in the slope deposits was highly chemically weathered in most positions. For this reason, the soil that is derived from the parent material, the drinking water and the plants were assumed to have lower concentrations of macronutrients, micronutrients as well as PTEs than the bedrock. Comparisons between the HR village Kaso and the LR village Panzato showed grus slope deposits to be more widespread in the LR than in the HR village, where the dominant parent material was pisolite slope deposits (see Chapter 3.2.1.2).

3.2.1.2 Pisolite slope deposits

In the lower positions of pediments and plains, slope deposits contained high contents of hard, round-shaped iron pisolites. There is a large number of hypotheses on the origin and development of these pisolites. According to Bennett et al. (1977a) and Burke and Durotoye (1970), the pisolite parent material in the northern guinea savanna soils is a weathering product of Pliocene ferricretes. According to Wall (1979), however, the pisolites are weathering products of secondary ferricretes that have developed after the Pliocene in positions of a fluctuating water table. In contrast, Tardy and Nahon (1985) stated that there are also pisolites in the West African soils that have developed in situ. As the pisolites found in the Kaduna study area showed significant peripheral fractures, were polished and very round-shaped, they were considered to be a slope deposits.

Table 3.4 Chemical composition of ferricretes in the Kaduna study area and in Cameroon.

[Based on (1) own unpublished data; (2) Tardy (1997)]

Study area	Bedrock	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_3	Ref.
		(mass%)										
Kaduna study area	Older Granites	52.5	0.4	10.9	27.7	< 0.1	< 0.1	< 0.1	< 0.1	0.1	0.3	(1)
Cameroon	Granite	24.7	0.6	15.9	46.3	< 0.1	0.1	0.1	0.4	0.1	na	(2)

(Ref.: reference; na: not available)

WDXRF analyses to determine the geochemical composition of the underlying ferricretes showed high concentrations of Fe and Al, while the concentrations of Mg, Ca, K and P were negligibly low (see Table 3.4). Such a geochemical composition is typical for ferricretes and has also been reported from other tropical areas (Dev & Rattan, 1998; Jaiyeoba, 1995; Malomo, 1983; Matheis & Pearson, 1982; Roquin et al., 1990). Assuming that the geochemical fingerprint of the ferricretes had further influenced the chemistry of the slope deposits, it would imply that soils developed on these slope deposits are not only relatively enriched in Fe and Al, but are also low in macronutrients and micronutrients. The pisolite slope deposits were therefore assumed to be geochemically different from the grus slope deposits.

Comparisons between two visited study sites, including the HR village Kaso and the LR village Panzato showed pisolite slope deposits to be the dominant parent material in the HR village, while in the LR village, grus slope deposits were more widespread (see Chapter 3.2.1). The soils in the HR village were therefore assumed to be unfavourable for crop production with regard to macronutrients, micronutrients as well as PTE concentrations.

3.2.1.3 River deposits

In close vicinity to the river valleys, which had mean heights of 620 m AMSL, slope gradients of less than 1° and were planar to slightly convex in form, river deposits were the dominant parent material of soil formation. Two types of river deposits were distinguished in the Kaduna study area: river deposits with sand-dominated grain sizes, which had deposited in marked banks known as river levees (Ahn, 1970) and clayey river deposits that had accumulated in flattish areas of the river floodplains. The latter were often found to have deposited in stratified layers.

All rivers rose in the Kaduna study area. Thus, the geochemistry of the river deposits was assumed to be comparable to all previously presented bedrock and parent-material types. However, according to Mahre et al. (2007) and Nwaedozie et al. (2011), river deposits in the Kaduna area typically contain high concentrations of PTEs, such as Cd or Pb. Adeyemo et al. (2008) and Jatau et al. (2008) assumed that these trace elements were brought in by fertilizer, herbicide, insecticide, trade-waste, domestic-sewage and refuse residues.

3.2.1.4 Aeolian deposits

In all the soils of the Kaduna study area, considerable contents of silt were found. According to Herrmann et al. (1996), high contents of silt are typical for West African soils and derive from dust deposits, brought in from the Chad Basin by north-eastern trade winds (harmattan) during the dry season between November and March (McTainsh, 1984). Depending on the specific geological sources, transport history and season of accumulation, the physical and chemical characteristics of these harmattan dusts can differ widely (Moreno et al., 2006).

Table 3.5 Background mineralogical composition in West African harmattan dust.
[Based on (1) Møberg et al. (1991); (2) Wilke et al. (1991); (3) Lyngsie et al. (2011)]

Study area	Qtz	K-Fs	Mca	Ca-Na-Fs	Apt	Ref.
	(%)					
Northern Nigeria	60.0	10.0	10.0	trace	-	(1)
Northern Nigeria	80.0	10.0	trace	7.0	trace	(2)
Northern Ghana	62.0	7.4	-	trace	-	(3)

(Apt: apatite; Ca-Na-Fs: Ca-Na-feldspar; K-Fs: K-feldspar; Mca: mica; Qtz: quartz; -: not traceable; trace: trace concentrations < 5%; Ref.: reference)

In northern Nigeria, the harmattan dust consists of approximately 12% fine sand, 57% silt and 25% clay (Møberg et al., 1991). The mineral composition is dominated in descending order by quartz > K-feldspars > mica > Ca-Na-feldspars > apatite (see Table 3.5).

Apatite ($Ca_{10}(PO_4)(OH,F,Cl)_2$), which is a common rock mineral in granites (Edmunds & Smedley, 2013), typically contains high concentrations of F (Reimann & Caritat, 1998), which in turn can have detrimental effects on bone health (Shorter et al., 2010). In such a way, high contents of apatite in Precambrian alkaline, coarse microcline-hornblende granites near Bolgatanga, in the Upper East Region of northern Ghana, are known to have caused dental fluorosis in local farmers' children (Smedley et al., 1995). However, as apatite concentrations in aeolian deposits are often not even traceable (see Table 3.5), the impact of apatite, derived from harmattan dusts, on the human bone health should be negligible in West Africa.

Apart from that, the aeolian deposits are known to be rich in important macronutrients, such as Ca, K, Mg and P and to be characterized by relatively high pH values and high cation-exchange capacities (Wilke et al., 1991). Furthermore, Adetunji et al. (2001) state that the dusts contain considerable concentrations of micronutrients and PTEs, such as Cu, Pb and Zn (see Table 3.6).

Adepetu et al. (1988) assume that these minor elements are derived not only from the parent materials of the source areas, but are brought into the dust also by the traffic and industry exhausts located along the dust transportation routes. According to Wilke et al. (1991), the macronutrient, micronutrient and PTE concentrations in the harmattan dust deposits are considerably higher than the bedrock- and parent material-derived nutrient and PTE concentrations in the environments of deposition.

Table 3.6 Background major element averages of harmattan dust in northern Nigeria.

[Major element data based on Wilke et al. (1991); minor element data based on Adetunji et al. (2001)]

Sample season	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_3	Cu	Zn	Pb
	(mass%)										(ppm)		
Rainy season	57.5	0.8	10.6	4.3	0.1	0.8	2.9	2.1	3.3	0.2	9.2	11.1	10.5
Dry season	65.0	0.9	10.0	3.8	0.1	0.6	1.9	1.1	3.0	0.2	11.7	14.1	16.5

(ppm: parts per million)

However, according to Breuning-Madsen et al. (2012) and Drees et al. (1992), only a small percentage of these elements is readily available for plants. As a result, effective surpluses in macronutrient and micronutrient concentrations can only be present in soils when sustainable land-use techniques, such as a fallow period and shifting cultivation, are used (Jaiyeoba, 2003; 1997). In most parts of West Africa, however, farmers are increasingly turning to tillage systems and permanent cultivation (Knez & Graham, 2013), making it questionable that these minor elements could have a significant impact on the environmental conditions of the northern Nigerian areas.

3.2.2 Distribution

Based on a 1:200000 topographical map (MTSAFRF, 1985), a draft of a parent-material map was created, roughly showing the areas of grus-slope-deposit, pisolite-slope-deposit and river-deposit distribution in the Kaduna study area (see Figure 3.7). Due to the small scale of the topographical map, no information was given on the location of the small rivers that every village in the Kaduna study area had access to. It therefore was not possible to display all the areas of river-deposit distribution in the map, apart from those found near the Kaduna River. Furthermore, as the exact distribution of the grus slope deposits and the pisolite slope deposits was not possible to predict from topographical maps, their respective extensions may be under- or over-represented in the rough-draft parent-material map (see Figure 3.7).

Based on this rough-draft parent-material map (see Figure 3.7), one may conclude that the CDR prevalence rates do not linearly depend on the parent-material distribution. Since, however, the deposits may be highly heterogeneously distributed at the different study sites, this map does not show the actual parent-material distribution, but should instead be considered an approximation.

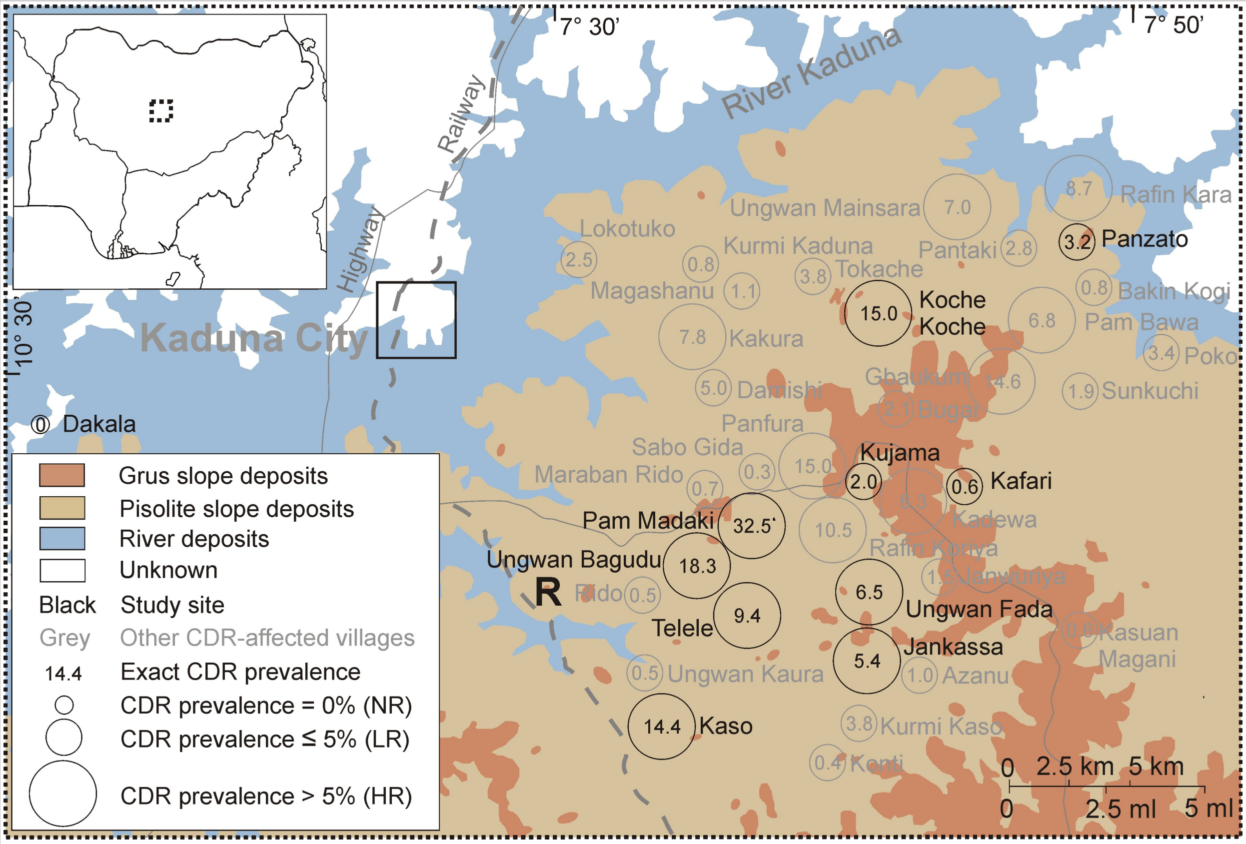

Figure 3.3 Rough-draft parent-material map of the Kaduna study area.
The map frame is equivalent to the study area; black bold R shows the location of an oil refinery; CDR: Ca-deficiency rickets.
[Topographical information based on MTSAFRF (1985), prevalence data based on Hakuri Matala and Sister Rita Schwarzenberger (personal communication)]

In summary, three main types of parent materials were identified in the Kaduna study area: grus slope deposits, pisolite slope deposits and river deposits. These three types of parent materials, which cover the basement bedrock, were identified as the actual substrates of soil formation and therefore as the main sources of macronutrients, micronutrients as well as PTEs in the soil-plant-human pathway in the Kaduna study area. The grus slope deposits were assumed to be geochemically comparable to the granitoid bedrock, thus containing relatively high concentrations of Si, K and F and low concentrations of Ca and Mg. The pisolite slope deposits were geochemically influenced by the chemical composition of the ferricretes, from where the pisolites have weathered. River deposits were found to be either sandy or clayey and both were expected to have high concentrations of macronutrients, micronutrients as well as PTEs. The distribution of the parent materials followed specific sequences of topography. Grus slope deposits were typically found in pediment positions; pisolite slope deposits covered the plains and river deposits were found in the river valleys. No clear link was found between the parent-material distribution and the CDR prevalence rates.

3.3 Land use

Land use, the human modification of the natural environment into fields, settlements and industrial areas (Foley et al., 2005), is known to potentially undermine the capacity of ecosystems (Lal, 2009). Unsustainable land use can further lead to a remobilization and redistribution of materials and elements, resulting in deficient macronutrient and micronutrient concentrations as well as anomalously high PTE concentrations in parts of a landscape (Davies & Mundalamo, 2010). Severe pollution of soils and water resources is widespread in developing countries, where environmental laws are often too weak to protect the environment (Agunwamba, 1998; Chrysanthus, 1997; Yabe et al., 2010). Finally, such element anomalies are known to have detrimental effects on the quality of locally produced human nutrition and thus may affect human health (Lal, 2009).

To analyse the land-use conditions in the Kaduna study area, field surveys were conducted for most parts of the study area and farmers of several villages were informally interviewed with regard to local land-use techniques, crops and fertilizer use. It thereby became apparent that the entire Kaduna study area is predominantly agriculturally used, while the exact percentages of the land that is actually cultivated remained unknown. According to Wall (1979), 10 to 34% of the rural Kaduna area was under cultivation in the 1970s. According to own estimates, however, at least 50% of the Kaduna land area is agriculturally used today. In particular, the areas near river valleys and pediments are the most intensively cultivated.

The potential natural vegetation of the northern guinea savanna was found to have almost been completely deforested to provide firewood and construction material, while only economically valuable tree species were spared. This kind of selective deforestation gave the study area a savanna parkland appearance. Woody species included *Acacia albida, Adansonia digitata*, *Annona senegalensis, Bombax costatum, Borassus aethiopum, Boscia senegalensis, Boswellia dalzielii, Butyrospermum parkii, Celtis integrifolia, Diospyros mespiliformis, Ficus ingens, Hildegardia barteri, Khaya grandifoliola, Mangifera indica, Parkia biglobosa, Piliostigma reticulatum, Securinega virosa, Vitex domina* and *Ziziphus mucronata.* The most ubiquitous pioneer plant was *Isoberlinia doka* (see Figure 3.4, right), which was found to be widespread on cleared areas and fallow grounds. To gain more income, some of the small-scale farmers have now started to sell timber from older trees to domestic lumber companies (see Figure 3.4, left), which has again accelerated the recent clearance of land.

In the entire Kaduna study area, sheet erosion and gully erosion of varying severeness were widespread, while erosion was found to be most intense in the northern parts of the study area, along the Kaduna River. According to Adewuyi (2009), at least 6% of the rural Kaduna area is affected by soil erosion. My own estimates were higher, at around 10%. As soil erosion is known to cause severe loss of soil fertility in those areas where material is removed (Eswaran et al., 1990; Jaiyeoba, 2003; Malgwi & Abu, 2011; Ridder et al., 2004), the soil fertility in the Kaduna study area should be low.

On the remaining land, labour-intensive, non-mechanized subsistence farming was practised with hand hoes and shovels. Since the economic incentives of the Royal Niger Company in the 1920s (Falola & Heaton, 2008), the local population has been encouraged to grow cash crops in steadily increasing amounts, including crops such as pepper (*Piper guineense*) (see Figure 3.4, middle), groundnuts (*Arachis hypogea*), ginger (*Zingiber officinale*) and rice (*Oryza glaberrima*). Over time, sorghum species (e.g. *Sorghum bicolour*) have been more and more replaced by maize (*Zea mays*), which is nowadays the staple food in the Kaduna study area. Instead of traditional crop varieties, maize is nowadays mostly cultivated as modern, hybrid and high-yield crop. Yams (*Dioscorea rotundata*), cassava (*Manihot utilissima*), sweet potatoes (*Ipomoea batatas*) and a variety of vegetables and fruits were grown as both food and cash crops.

An increase in cash-crop production is known to result in a one-sided removal of macronutrients from soil (Brady & Weil, 1999; Phillips-Howard & Lyon, 1994), especially of the elements N > K > P > Mg > Ca, in descending order (Ahn, 1970; Putthacharoen et al., 1997; Scheffer & Schachtschabel, 2002). It is therefore possible that an increase in market-oriented agriculture has further exacerbated soil depletion in the Kaduna study area.

Figure 3.4 Land use and human impact in the Kaduna study area.
From left to right: deforestation in Kaso village, pepper cash crop cultivation along the Kaduna River, gully erosion in Panzato village.
(Left and middle photo provided by Prof. Barbara Sponholz)

Based on a population growth rate of 4% among the population of the Kaduna study area since the 1970s (Adedayo & Sanda, 2011; Meek, 1971), the land percentages used for continuous cash crop cultivation were reported to have steadily increased in the Kaduna study area. In contrast, local farmers reported fallow years to have significantly decreased from 40 years previously to approximately 10 to 20 years per field nowadays. As continuous cultivation and shortages of fallow periods are generally believed to aggravate soil nutrient deficiencies (Drechsel et al., 2001; Heathcote & Stockinger, 1970; Jaiyeoba, 2003; 1997; Lal, 1997; Nwoke et al., 2004), the increase in permanent cultivation was thought to be responsible for the degradation of the soils in the Kaduna study area. The reported steady spread of *Striga hermonthica,* which is a low-soil-fertility-loving parasitic indicator plant (Emechebe et al., 2004), may support this assumption.

To combat the steady spread of striga, local farmers have nowadays started to use herbicides. To protect their crop plants, they also use pesticides, insecticides and fungicides with unknown chemical composition and in unknown amounts. However, such substances are known to not only prevent, control or destroy pests but also to contaminate soil and groundwater (Fuge, 2013) and to be detrimental to soil biota (Ahonsi et al., 2004). However, as the amounts of plant-protection products used in the Kaduna study area were assumed to be low due to the poverty among the local population, a severe PTE contamination of the Kaduna study area's ecosystems was considered unlikely.

Apart from plant-protection products, different types of inorganic fertilizers are used in the Kaduna study area. These include NPK, superphosphate, compound and urea. Fertilizer use was found to be almost entirely restricted to applications of N, P and K, while applications of Ca, Mg or Se were more or less neglected (see Table 3.7) due to high prices or unavailability. According to Graham and Welch (1996), such one-sided fertilizer use is known to bring about a leaching without return of macronutrients and micronutrients, such as Ca, Mg or Se.

P fertilizers manufactured from apatite-rich rocks may further lead to a significant increase in PTEs in soils (Fuge, 2013), including an increase in the elements F, Cd, Pb or Sr (Stacey et al., 2010). Pickering (1985) and Larsen and Widdowson (1971), for instance, reported total soil F concentrations to increase by 70% after intensive P fertilization. Agbenin (2002), Cronin et al. (2000) and Kparmwang and Malgwi (2009) reported similar trends from other fertilized and agriculturally used regions in Nigeria.

Table 3.7 Chemical composition of fertilizers used in the Kaduna study area.
[Macronutrient concentrations based on Gabriel (unpublished, 2012); trace element concentrations based on Fuge (2013) and Stacey et al. (2010)]

Fertilizer	**N**	**P**	**K**	**Ca**	**Mg**	**Se**	**Cd**	**F**	**Pb**	**Sr**
	(%)									
Superphosphate ($Ca(H_2PO_4)_2$)	-	7.0-9.5	-	18.0-21.0	-	< 0.1	< 0.1	1.3-3.0	< 0.1	< 0.1
Compound (NPK)	20.0	4.4	8.3	-	-	-	< 0.01	< 1.3	< 0.001	< 0.01
Golden (NPK)	15-27	5.2-6.6	8.3-14.1	-	-	-	< 0.01	< 1.3	< 0.001	< 0.01
Urea ($CO(NH_2)_2$)	46.0	-	-	-	-	-	-	-	-	-
Animal manure	2	0.7	1.7	2.9	0.6	< 0.1	-	-	-	< 0.01

(-: not traceable)

However, high concentrations of F or other PTEs in the soils of the Kaduna study area due to fertilizer use are unlikely, as the fertilizer amounts used per hectare were reported to be very low. Such insufficiencies in fertilizer use are known from many other areas in the northern guinea savanna, even throughout the African continent and typically are a consequence of poor economic conditions (Bationo et al., 2007; Chianu & Tsujii, 2004; Manyong et al., 2001; Mwangi, 1997).

Apart from potential element deficiencies or toxicities caused by agricultural use, industrial processes and wastes are known to potentially increase trace element concentrations in the environment (Fuge, 2013). In the Kaduna study area, three sources, which may contribute to such trace element influxes, were identified: fossil fuel combustion due to motorcycle use (see Figure 3.5, left), scattered waste disposal (see Figure 3.5, right) and refinery exhaust (see Figure 3.5, middle), originating from the largest inland oil refinery in Nigeria, which is located in the western part of the Kaduna study area (see Figure 3.1).

More precise observations in the Kaduna study area, however, showed that motorcycle use and scattered waste disposal were negligibly low as compared to those in urban areas (Elaigwu et al., 2007; Nriagu et al., 1997). Heavy soil element contamination due to fossil fuel combustion has been reported in Kaduna City (Akeredolu, 1989; Anake et al., 2009;

Anikwe & Nwobodo, 2002; Okunola et al., 2010; Oyewale & Funtua, 2002) but is unknown in the rural Kaduna areas.

Figure 3.5 Potential sources of industrial pollution in the Kaduna study area.
From left to right: fossil-fuel combustion, refinery exhaust and scattered waste disposal.

With regard to the Kaduna oil refinery, high concentrations of PTEs, such as Pb, Cd, Cu and Zn, have been identified in the near vicinity of the industrial complex (Cetin et al., 2003; Ndiokwere & Ezihe, 1990; Odeyemi & Ogunseitan, 1985), but are unlikely to be elevated in environments outside a radius of 5 km from the complex (Bako et al., 2004; Sonibare et al., 2007). Moreover, since the effluents of the oil refinery are dewatered in a downstream direction (Onwumere & Oladimeji, 1990; Wake, 2004), a fluvial influx of PTEs into the river systems of the Kaduna study area is unlikely.

To summarize, the Kaduna study area has been affected by a strong growth in population over the last few decades. Prompted by economic incentives, the local farmers are increasingly growing cash crops and have intensified permanent cultivation. This has led to high deforestation and agricultural use in the study area which may have resulted in soil fertility loss. To enhance crop growth and to protect crop health, fertilizers, pesticides, herbicides and fungicides are used in small amounts. The industrial impacts in the Kaduna study area are low, making severe environmental pollution of the local ecosystems unlikely.

3.4 Soils

3.4.1 Types

In the Kaduna study area, four main soil types were identified: Lixisols, Acrisols, Plinthosols and Fluvisols. The typical characteristics of these soil types as well as their typical physico-chemical characteristics as found in the Kaduna study area are presented in the following.

3.4.1.1 Lixisols

Lixisols are typical savanna soils and have been reported from many areas in Nigeria and West Africa (Faure & Volkoff, 1998; Lemuel, 2012; Sonneveld, 1996; Young, 1979). Lixisols are known for their low capacity to store macronutrients and often have a low aggregate stability. Once cultivated, Lixisols are highly susceptible to erosion and regenerate only very slowly once physically or chemically deteriorated. The typical characteristics of this soil type are higher clay contents in the subsoil than in the topsoil, a high BS and high contents of low-activity clays at certain depths (IUSS Working Group, 2006a).

In the Kaduna study area, Lixisols had typically developed on upper pediment positions and were underlain by grus slope deposits. In Table 3.8 such a Lixisol is presented. This soil was a typical Lixisol in two ways. Firstly, it represented typical Lixisol physicochemical characteristics, with a mean BS greater than 50% and a mean CECpot of less than 8 cmol kg^{-1}. Secondly, it showed an argic, clay-enriched B horizon and high contents of weathered granitoid grus in the lower soil position, which may have been the source of the high cation contents in this soil. The soil was further found to be covered by a 20-cm-thick colluvium (prefix qualifier: colluvic), which was identified by its greyish-brown soil colour and relatively high pH values, high OC concentration and high BS (see Table 3.8). This A horizon was ploughed (p) to a depth of 20 cm. Under the A horizon, an older soil layer (2) was found. In this 2B horizon, coatings were identified on soil particles and interpreted as illuvial clay accumulation (t). An eluvial horizon, however, which must once have covered this clay-enriched 2B horizon, was not identified and was assumed to have been eroded. Such erosional and colluvial phenomena were found to be typical for soils in and around the LR village Panzato, where slopes were slightly steeper than in the HR village Kaso (see Chapter 3.3). A clear massive (MA), subangular blocky (SB) soil structure (w) was found and so this diagnostic 2Bt horizon (*) was labelled with the letters 2Btw*. With increasing depth, the influence of the grus-slope-deposit parent material became visible by a sandy clay texture and a relatively high CECpot. Highly weathered quartz, feldspar and mica minerals were found in the lower parts of the soil profile. The soil structure (w) was still massive and subangular blocky. The soil colour was reddish brown, presumably due to oxidation (o). This horizon was marked with 2Bwo (see Table 3.8). No further meaningful characteristics (prefix qualifier: haplic) were found in this soil. The soil type as presented in Table 3.8 therefore was named as Haplic Lixisol (colluvic) (see Table 3.8).

Table 3.8 Selected physicochemical soil characteristics of Haplic Lixisol (colluvic) in the LR village Panzato.

A detailed soil-type description as well as additional information on laboratory results are given in Appendices A and B.

	Horizon	**Depth (cm)**	**Texture**	**Coatings**	**Mottles**	**Colour (Munsell)**	
	Ap	0-20	sandy loam	none	none	10YR 5/2	
	2Btw*	20-50	clay loam	common	few, fine, faint	5YR 4/6	
	2Bwo	50+	sandy clay	none	few, fine, faint	5YR 3/4	
	Structure	**pH**	**OC (%)**	**BS (%)**	**CECpot (cmol kg^{-1})**	**Minerals**	
						Parent material	**Clay**
	CR	5.3	1.0	60.7	6.4	Qtz > Fs > Mca	Kln > Ill
	MA, SB	4.8	0.5	57.9	11.9	Qtz > Fs > Mca	Kln > Ill
	MA, SB	4.7	0.2	50.7	10.1	Qtz > Fs > Mca	Kln > Ill

(*: diagnostic soil horizon; Ill: illite; Kln: kaolinite; Qtz: quartz; Fs: feldspar; Mca: Mica; CR: crumbly; MA: massive; SB: subangular blocky; LR village: CDR prevalence rate ≤ 5%)

Based on these Lixisol characteristics, the Lixisols found in the study area were assumed to bear a risk of causing macronutrient deficiencies in crops, especially in the LR village Panzato, where erosional and colluvial processes were widespread.

3.4.1.2 Acrisols

Similar to Lixisols, Acrisols are characterized by argic B horizons and high contents of low-activity clays, but they have a low BS. The productivity of Acrisols in tropical soils is often limited, as this soil type has little capacity to recover from overcultivation and excessive macronutrient and micronutrient removal (IUSS Working Group, 2006a), a problem that has been reported from many West African Acrisol areas (Faure & Volkoff, 1998; Young, 1979).

Furthermore, Acrisols are often acidic and tend to bear toxic concentrations of Al. However, when sufficiently enriched in organic matter and lime, Acrisols can develop a considerably high CECpot (IUSS Working Group, 2006a).

In the study area, three types of Acrisols were found: those that developed on grus slope deposits (see Table 3.9), those that developed on pisolite slope deposits (see Table 3.10) and those that were additionally influenced by river deposits and hydromorphic conditions (see Table 3.11).

A typical Acrisol that had developed on grus slope deposits in the LR village Panzato is shown in Table 3.9. The ploughed A horizon (Ap) had a sandy loam texture, a pale brown colour, normal OC, relatively high pH values and a high CECpot. At a depth of 10 cm, faint signs of capillary fringing mottling (l), reflecting colours between strong brown (7.5YR 5/6) and yellowish red (5YR 5/8) occurred. Due to the mottling, the horizon was termed a Bl horizon. With increasing depth, clay contents increased and coatings (t) became visible. In the following horizon, the texture and mineral composition changed markedly, indicating that this 2B horizon was an older soil horizon. Furthermore, this 2B horizon had a lumpy soil structure (LU), relatively high clay contents and showed coatings (t) on soil-particle surfaces (see Table 3.9). The entire soil profile was dominated by a sandy soil texture (suffix qualifier: arenic). No further meaningful characteristics were found in the soil (prefix qualifier: haplic). The soil type as presented in Table 3.9 was named Haplic Acrisol (arenic).

Table 3.9 Selected physicochemical soil characteristics of Haplic Acrisol (arenic) in the LR village Panzato.

A detailed soil-type description as well as additional information on laboratory results are given in Appendices A and B.

	**Horizon**	**Depth (cm)**	**Texture**	**Coatings**	**Mottles**	**Colour (Munsell)**	
	Ap	0-10	sandy loam	none	none	10YR 6/4	
	Bl	10-30	sandy loam	none	few, fine, faint	7.5YR 5/6-5YR 5/8	
	Bt*	30-80	sandy clay loam	few	few, fine, faint	7.5YR 5/6-5YR 4/6	
	2Bt	80+	clay loam	few	few, fine, distinct	7.5YR 5/8-5YR 4/6	
	Structure	**pH**	**OC (%)**	**BS (%)**	**CECpot (cmol kg^{-1})**	**Minerals**	
						Parent material	**Clay**
	CR	5.6	0.7	46.3	7.4	Qtz > Fs > Mca	Kln > Ill
	nd	5.4	0.3	65.8	2.9	Qtz > Fs > Mca	Kln > Ill
	LU	4.9	0.3	40.0	8.3	Qtz > Fs > Mca	Kln > Ill
	MA, SB	4.7	0.1	37.3	8.0	Qtz > Fs > Mca	Kln > Ill

(*: diagnostic soil horizon; Ill: illite; Kln: kaolinite; Qtz: quartz; Fs: feldspar; Mca: Mica; CR: crumbly; LU: lumpy; MA: massive; SB: subangular blocky; nd: not determined; LR village: CDR prevalence rate ≤ 5%)

Acrisols that had developed on pisolite slope deposits contained high contents of pisolites, had argic, clay enriched B horizons, a low BS and high contents of low-activity clays (IUSS Working Group, 2006a).

A typical Acrisol that had developed on the pisolite slope deposits from the HR village Kaso is presented in Table 3.10. The uppermost A horizon of this Pisoplinthic Acrisol was not ploughed, as with the other soil types presented here. Instead, the soil was kept under fallow, which resulted in high concentrations of organic matter (h) and OC and a brown soil colour (7.5YR 5/3) in the A horizon. This Ah horizon was furthermore dominated by pisolites (c). In deeper soil positions, the clay contents increased and coatings (t) were discovered on soil-particle surfaces. This diagnostic Bt* horizon had a BS clearly below 50% and a low CECpot. In deeper depths, the soil colour became increasingly reddish, which was assumed to be due to oxidation (o). With further increasing depth, the soil structure (w) became massive and subangular blocky. While clay contents increased with depth throughout the soil profile, the levels of pH significantly decreased. The entire profile was dominated by pisolites (c). The soil colour was redder than 7.5YR and consequently, the soil was marked with the suffix qualifier chromic (see Table 3.10). The entire soil profile was dominated by more than 40% pisolites (prefix qualifier: pisoplinthic). The soil type as presented in Table 3.10 was therefore named Pisoplinthic Acrisol (chromic).

Table 3.10 Selected physicochemical soil characteristics of Pisoplinthic Acrisol (chromic) in the HR village Kaso.

A detailed soil-type description as well as additional information on laboratory results are given in Appendices A and B.

	Horizon	**Depth (cm)**	**Texture**	**Coatings**	**Mottles**	**Colour (Munsell)**	
	Ahc	0-10	clay loam	none	none	7.5YR 5/3	
	Bto*	10-30	clay loam	faint	nd	7.5YR 6/6	
	2Bw	30-60+	clay	none	none	7.5YR 6/6	
	Structure	**pH**	**OC (%)**	**BS (%)**	**CECpot (cmol kg^{-1})**	**Minerals**	
						Parent material	**Clay**
	CR	5.0	1.2	38.0	12.5	Ps	Kln > Ill
	nd	4.2	0.5	30.5	9.7	Ps	Kln > Ill
	MA, SB	4.0	0.4	22.7	10.3	Ps	Kln > Ill

(*: diagnostic soil horizon; Ill: illite; Kln: kaolinite; Ps: pisolites; CR: crumbly; MA: massive; SB: subangular blocky; nd: not determined; HR village: CDR prevalence rate > 5%)

Where Acrisols were found in lower slope positions, influenced by fluctuating water tables, the Acrisols were marked with the prefix qualifier gleyic. Apart from a gleyic and thus mottled colour spectrum, these Gleyic Acrisols often contained high contents of silt. Furthermore, the typical physicochemical characteristics included a low BS, argic B horizons and high contents of low-activity clays (IUSS Working Group, 2006a).

A typical Gleyic Acrisol as found in the HR village Kaso is presented in Table 3.11. This Gleyic Acrisol was ploughed (p) in the upper A horizon. With increasing depth, the clay contents increased slightly and the soil colour became redder, presumably due to oxidation (o). Coatings were visible (t) on soil-particle surfaces. The CECpot was only 8 cmol kg^{-1} and the BS was clearly less than 50%. This diagnostic Bto* horizon, which had a platy (PL) to lumpy soil structure, was followed by horizons with significantly higher clay contents (2). At a depth of 25 cm, the influence of the water table became visible by gleyic mottling (g) and decreased pH values. The dominant soil colour was oxidized (o) to greyish orange (10YR 7/4). At deeper positions, at a depth of 60 cm+, the mottling and gleyic colour pattern (g) increased, while the soil colour was pale greyish orange (10YR 6/2), which was interpreted as due to reduction (r). The pH values, OC concentration and BS clearly decreased throughout the entire soil profile (see Table 3.11). The entire soil profile was dominated by a silty soil texture (suffix qualifier: siltic). The soil type as presented in Table 3.11 was therefore named Gleyic Acrisol (siltic).

Table 3.11 Selected physicochemical soil characteristics of Gleyic Acrisol (siltic) in the HR village Kaso.
A detailed soil-type description as well as additional information on laboratory results are given in Appendices A and B.

Horizon	Depth (cm)	Texture	Coatings	Mottles	Colour (Munsell)	
Ap	0-15	silt loam	none	none	10YR 6/2	
Bto*	15-25	silt loam	few	none	10YR 6/3	
2Cog	25-60	silt clay loam	few	few, fine, faint	10YR 7/4	
2Crg	60-80	silty clay	few	many, medium, faint	10YR 7/4-10YR 6/2	
Structure	**pH**	**OC (%)**	**BS (%)**	**CECpot (cmol kg^{-1})**	**Minerals**	
					Parent material	**Clay**
LU	4.2	0.8	26.9	9.6	Qtz, Fs, Mca, Ps	Kln > Ill
PL, LU	4.3	0.7	31.6	8.0	Qtz, Fs, Mca, Ps	Kln > Ill
SB	3.9	0.4	28.9	10.5	Qtz, Fs, Mca, Ps	Kln > Ill
AB	3.9	0.4	15.0	9.5	Qtz, Fs, Mca, Ps	Kln > Ill

(*: diagnostic soil horizon; Ill: illite; Kln: kaolinite; Qtz: quartz; Fs: feldspar; Mca: Mica; Ps: pisolites; AB: angular blocky; LU: lumpy; PL: platy; SB: subangular blocky; HR village: CDR prevalence rate > 5%)

In the Kaduna study area, where liming was absent and fertilizers were used only in small amounts (see Chapter 3.3), Acrisols were assumed to be unsatisfactory sites for agricultural use, but were cultivated by local small-scale farmers in the Kaduna study area anyway.

3.4.1.3 Plinthosols

The soils developed on upper plains, where pisolite slope deposits and aeolian deposits were the dominant parent materials, were classified as Plinthosols. Al and Fe play a major role in the formation of this soil type, in which kaolinite is the major clay mineral. Plinthosols are of poor natural fertility, while high contents of pisolites or plinthite pose serious limitations to crop root development. In many areas of Africa, crops grown on Plinthosols suffer from drought effects (IUSS Working Group, 2006a). In Nigeria, Plinthosols are a widespread soil type (Delaure, 1998; Raji et al., 2011; Vanlauwe et al., 2002).

Table 3.12 Selected physicochemical soil characteristics of Haplic Plinthosol (hyperdystric, clayic) in the HR village Kaso.
A detailed soil-type description as well as additional information on laboratory results are given in Appendices A and B.

Horizon	Depth (cm)	Texture	Coatings	Mottles	Colour (Munsell)	
Ahc	0-5	clay	none	none	7.5YR 6/6	
Btv*	5-40	clay	faint	none	7.5YR 6/6	
Bov	40-80	heavy clay	none	none	2.5YR 4/8	
Structure	**pH**	**OC (%)**	**BS (%)**	**CECpot (cmol kg^{-1})**	**Minerals**	
					Parent material	**Clay**
CR	4.2	1.3	26.2	13.5	Ps	Kln > Ill
CR	4.0	0.4	6.3	12.0	Ps	Kln > Ill
MA, SB	4.0	0.4	5.2	12.1	Ps	Kln > Ill

(*: diagnostic soil horizon; Ill: illite; Kln: kaolinite; Ps: pisolites; MA: massive; CR: crumbly; SB: subangular blocky; HR village: CDR prevalence rate > 5%)

A typical Plinthosol as developed on pisolite slope deposits in the HR village Kaso is described in Table 3.12. The A horizon was not ploughed, meaning that the organic matter (h) and OC concentrations were still relatively high in the subsoil. In deeper positions, clay contents increased slightly and coatings became visible (t). Apart from pisolites, plinthite was found (v), which is an Fe-rich, humus-poor mixture of kaolinitic clay that can become irreversibly hard when dried (IUSS Working Group, 2006a). The diagnostic Btv* horizon was followed by another B horizon with a deep red colour (2.5YR 4/8) due to oxidation (o). The pH values, OC concentrations and CECpot and BS decreased with depth, while the mean BS was below 20% (suffix qualifier: hyperdystric). The clay contents were high throughout the profile and for this reason the soil was additionally marked with the suffix qualifier clayic. The main clay mineral in this soil type was kaolinite (Table 3.12). No further meaningful characteristics were identified in this soil (prefix qualifier: haplic). The soil type as presented in Table 3.12 therefore was named Haplic Plinthosol (hyperdystric, clayic).

3.4.1.4 Fluvisols

Fluvisols are azonal soils which have developed on alluvial deposits, which is the characteristic that differentiates them from Gleysols (IUSS Working Group, 2006a). Due to the high water table, Fluvisols are commonly used for rice cultivation (IUSS Working Group, 2006a). The natural fertility of Fluvisols in tropical areas is usually not as high as in temperate regions. This is mainly due to the lack of macronutrients in the alluvial parent materials and the tropical-climate-induced rapid destruction of organic matter (Young, 1976). Furthermore, some Fluvisols tend to severe acidity and Al toxicity and often are sinks for industry-derived or agriculture-derived PTEs (Oluwatosin et al., 2008). In northern Nigeria, Fluvisols of this type are widespread (Delaure, 1998; Fagbami et al., 1985a; Faure & Volkoff, 1998; Raji et al., 2011).

In the Kaduna study area's lowlands and river valleys, the dominant soil type was Fluvisols. All the Fluvisols in the study area showed clear signs of groundwater influence and had gleyic colour patterns with signs of Fe reduction within 50 cm of the soil surface. Therefore, the Fluvisols in the Kaduna study area were always marked with the prefix qualifier gleyic. Where the BS was found to be below 50% between 20 and 100 cm from the soil surface, the Fluvisols were marked with dystric as a suffix qualifier. Basically, two types of Gleyic Fluvisols were found: those that developed in locations near river valleys and those that developed further away in sandy river levees (see Chapter 3.2.1.3). This difference was expressed by the suffix qualifiers siltic and arenic, respectively.

A typical Gleyic Fluvisol (siltic), as found in the study area, is presented in Table 3.13. This Gleyic Fluvisol was found at a 50-m distance from a dry-season river flow in the HR village Kaso. The soil profile was, also in deeper positions, mostly dry, but according to the statements from the local farmers, the Fluvisol as presented in Table 3.13 is water-logged during the rainy season. The fluxes of the water table were found to have led to the development of mottles throughout the soil profile. In the uppermost horizon, which was ploughed (p) and which had a layered soil structure (LY), the soil colours were found to range from brown to dark yellowish brown. The pH values were relatively high, while the CECpot was low and the BS was less than 50%. With increasing depth, the contents of silt increased, evident as increased gleyic (g) mottle patterns, including slightly redder soil colours due to oxidation (o). With further increasing depth, the clay contents and OC concentrations increased and mottles became abundant. Based on these findings, the Fluvisols of the Kaduna study area were assumed to be minor sites for crop production.

Table 3.13 Selected physicochemical soil characteristics of Gleyic Fluvisol (dystric, siltic) in the HR village Kaso.
A detailed soil-type description as well as additional information on laboratory results are given in Appendices A and B.

	**Horizon**	**Depth**	**Texture**	**Coatings**	**Mottles**	**Colour**	
		(cm)				**(Munsell)**	
	Ap	0-15	clay loam	none	few, fine, faint	10YR 5/2-10YR 4/6	
	Bog*	15-45	silt loam	none	many, fine, faint	10YR 4/3-10YR 4/6	
	Cog	45-90	silt clay loam	none	abundant, fine, faint	10YR 4/3-10YR 4/6	
	Structure	**pH**	**OC**	**BS**	**CECpot**	**Minerals**	
			(%)	**(%)**	**(cmol kg^{-1})**	**Parent material**	**Clay**
	LY	5.1	0.4	8.4	40.5	Qtz, Fs, Mca, Ps	Kln > Ill
	AB	4.6	0.7	8.5	35.5	Qtz, Fs, Mca, Ps	Kln > Ill
	SB	4.5	1.4	14.6	28.0	Qtz, Fs, Mca, Ps	Kln > Ill

(*: diagnostic soil horizon; Ill: illite; Kln: kaolinite; Qtz: quartz; Fs: feldspar; Mca: mica; Ps: pisolites; AB: angular blocky; LY: layered; SB: subangular blocky; HR village: CDR prevalence rate > 5%)

In summary, four main soil types were identified in the Kaduna study area: Lixisols, Acrisols, Plinthosols and Fluvisols. The potential natural soil fertility of these soil types decreased in the order Lixisols > Fluvisols > Acrisols > Plinthosols. Compared to the soil surveys of other scientists, these soil types were found to be typical for areas located in the northern guinea savanna of Nigeria.

3.4.2 Distribution

In the Kaduna study area, the soil-type distribution was linked to specific slope positions and, most often, to specific parent materials.

In such a way, Lixisols were found to have developed in upper pediment positions on grus slope deposits. Acrisols were found in lower pediment as well as in lower plain positions and had developed on grus and pisolite slope deposits, sometimes enriched in river deposit material. Plinthosols were the dominant soil type in the upper plains, where pisolite slope deposits were the dominant parent material. Fluvisols were the typical soil type in the river valleys, where river deposits had accumulated as the dominant parent material (see Tables 3.14 and 3.15).

These results were confirmed by extensive Puerckhauer soil sampler analyses, which were conducted punctually in all the study sites (see Chapter 2.2). Furthermore, similar parent material - slope form - soil type interdependencies have also been described in other areas of northern Nigeria (Faure & Volkoff, 1998).

An idealized toposequence of the typical parent materials, slope forms and soil types as found in the Kaduna study area is presented in Figure 3.6.

Table 3.14 Parent materials, slope positions and soil types in the HR village Kaso.

Primary parent materials	Secondary parent materials	Slope position	Soil type	Horizon	Lower horizon depth (cm)
Grus slope deposits	Aeolian deposits	Upper pediments	Epileptic Lixisol (arenic)	Ap/Bt*	10/40+
			Haplic Lixisol	Ap/Bt*	10/10+
	River and aeolian deposits	Lower pediments	Gleyic Acrisol (chromic)	Ap/Btg*	10/70+
Pisolite slope deposits	Aeolian deposits	Lower plain	Pisoplinthic Acrisol (chromic)	Ap/Bto*/2Bov/3Cv	15/45/55/55+
			Gleyic Acrisol (siltic)	Ap/Bto*/2Cog/2Crg	15/25/60/80
			Pisoplinthic Acrisol (chromic)	Ahc/Bt*/2Bw	10/30/60+
	River and aeolian deposits	Upper plain	Haplic Plinthosol (dystric)	Apc/Bv*/Csmv	15/30/30+
			Haplic Plinthosol (hyperdystric, clayic)	Ahc/Btv*/Bov	5/30/80
River deposits (clayey)	Aeolian deposits	River Valley	Gleyic Fluvisol (dystric, arenic)	Ap/Bg/2Bsg*	25/80/100+
			Gleyic Fluvisol (dystric, siltic)	Ap/Bsg	20/60+
			Gleyic Fluvisol (dystric, siltic)	Ap/Bog*/Cog	15/45/90

(*: diagnostic horizon; HR village: CDR prevalence rate > 5%)

Table 3.15 Parent materials, slope positions and soil types in the LR village Panzato.

Primary parent materials	Secondary parent materials	Slope position	Soil type	Horizon	Lower horizon depth (cm)
Grus slope deposits	Aeolian deposits	Upper pediment	Haplic Lixisol (chromic)	Ap/Bt*/2Btw	5/55/55+
			Haplic Lixisol (colluvic)	Ap/2Btw*/2Bwo	20/50/50+
	River and aeolian deposits	Lower pediment	Haplic Acrisol (arenic)	Ap/Bo/Bto*/2Bo	15/30/50/50+
			Haplic Acrisol	Ap/Bto*/Bwo	10/45/45+
			Haplic Acrisol (arenic)	Ap/Bl/Bt*/2Bt	10/30/80/80+
Pisolite slope deposits	River and aeolian deposits	Lower Plain	Pisoplinthic Acrisol	Ah/Bt*/2Bt	10/25/25+
River deposits (sandy)	Aeolian deposits	River Valley	Gleyic Fluvisol (arenic)	Ap/Bg/2Bsg*/3Cr	20/35/80/95

(*: diagnostic horizon; LR village: CDR prevalence rate ≤ 5%)

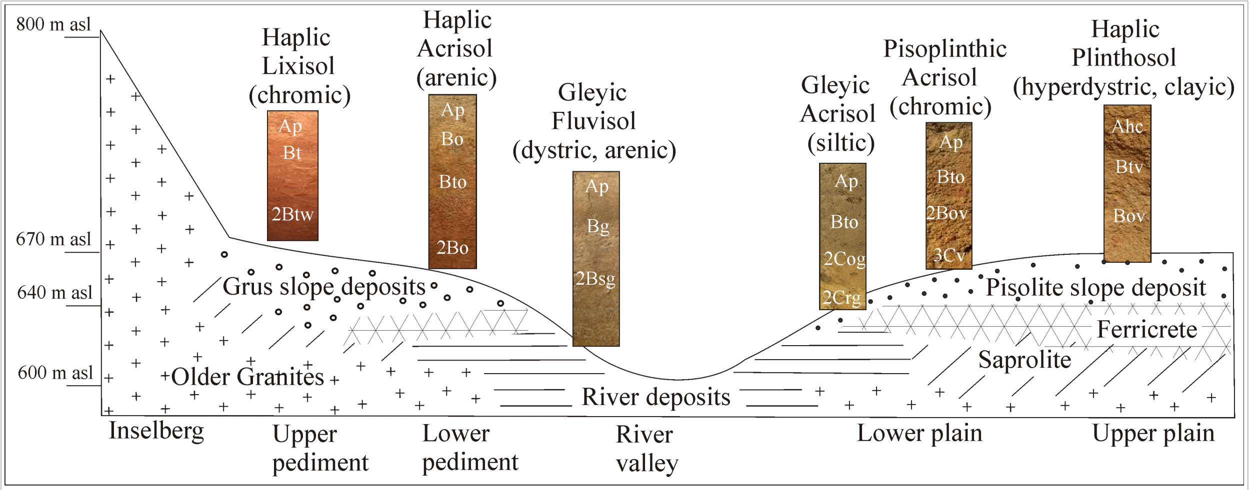

Figure 3.6 Idealized soil toposequence in the Kaduna study area.

3.4.3 Texture

To determine the quality of the soils in the Kaduna study area, analyses on the physical characteristics, such as particle-size distribution or soil depth, are required (Landon, 1991; Arshad & Martin, 2002). Information regarding particle sizes provides clues not only about parent material (Scheffer & Schachtschabel, 2002) but also about soil chemical characteristics (Pagel, 1981). For example, coarse-textured soils are known to lack both nutrient and water holding capacities (Alloway, 2013), while fine textured soils, for instance, often have structural and infiltration problems (Malgwi & Abu, 2011).

In the Kaduna study area, the soils in general were slightly sandy, especially at the surface. According to Jaiyeoba (1995) and Nwoke et al. (2004), the sandy grain size in the northern Nigerian soils is due to coarse-grained granites constituting the underlying bedrock. According to Bennett et al. (1977a), however, vertical and lateral clay eluviation and clay dissolution as well as surface erosion are responsible for these coarse-textured soil surfaces.

Apart from sand, high contents of silt (25-40%) were identified in all the soils from the study area, mostly independently of soil depth. According to Bennett (1980), Herrmann et al. (1996) and Jaiyeoba (2003), such high silt contents are typical for soils of the northern guinea savanna and are due to steady aeolian deposit influxes, which have been transported into the deeper soil positions over time by different biophysical processes.

Clay contents correlated positively with soil depth, while the highest contents were found in B horizons. According to Bennett et al. (1977a), who performed microscope investigations on soil samples from the Kaduna area, these argilic horizons have rather developed due to clay illuviation than to pedogenic processes. Where clay contents were high in A horizons, the ploughing processes or influxes of clayey river deposits were assumed to have brought in the higher clay contents.

The mean depths of the soils were found to vary depending on the slope position, while the mean depths of the soils on the pediments, plains and river valleys were ± 40 cm, ± 50 cm and ± 70 cm, respectively (see Table 3.16).

Table 3.16 Soil depth and particle-size distribution of soils in the Kaduna study area.

Detailed soil-type-specific data are given in Appendix B.

Study site	Parent material	Horizon	n	Depth	Sand	Silt	Clay
				(cm)	(%)		
HR village	Grus slope deposits	A	3	0-10	63.7	23.6	12.7
		B	3	10-40	41.7	25.0	33.3
	Pisolite slope deposits	A	5	0-15	28.6	42.2	29.2
		B	8	15-50	23.7	38.3	38.0
		C	4	50+	20.0	39.4	38.6
	River deposits (clayey)	A	3	0-20	15.7	46.7	37.6
		B	4	20-70	28.0	47.0	25.0
		C	1	70+	12.0	37.0	31.0
HR village mean					29.1	39.0	31.9
LR village	Grus slope deposits	A	5	0-15	53.2	33.4	13.4
		B	12	15-60	38.7	28.8	32.5
	Pisolite slope deposits	A	1	0-10	71.0	23.0	6.0
		B	2	10-25	54.5	25.5	20.0
	River deposits (sandy)	A	1	0-20	58.0	29.0	13.0
		B	2	20-80	56.0	26.5	17.5
		C	1	80+	77.0	14.0	9.0
LR village mean					48.1	28.5	23.4

[Sand: 2000-63 µm; Silt: 63-2 µm; Clay: < 2 µm; n: number of samples; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

Comparisons between the soils in the HR and LR villages showed significant differences in the soil textures. While in the HR village Kaso, the soils were dominated by a silty texture, the soils in the LR village Panzato were mostly sandy, especially in the topsoils. In some positions, the mean silt-content difference of the soils in the HR and LR villages was greater than 10% (see Table 3.16). This difference was assumed to be caused by differences in the dominant parent material (see Chapter 3.4.2): while pisolite slope deposits were widespread in the HR village, soils in the LR village had developed mainly on grus slope deposits, which led to a more sandy texture. In addition, higher erosion rates in the LR village (see Chapter 3.3) may have caused the soils in the LR village to have lower silt contents than the soils in the HR village.

All the soils in the Kaduna study area exhibited textures typical for soils that have developed on granites and gneisses in northern Nigeria: sandy topsoils, clayey subsoils and relatively high contents of silt (Malgwi & Abu, 2011; Møberg & Esu, 1991; Valette & Ibanga, 1984). Predominantly high contents of clay are found only in areas where metasediments constitute the typical bedrock, while extremely high sand contents are typical for areas underlain by sandstone bedrock (see Table 3.17).

Assessing the textural characteristics from the soils of the Kaduna study area showed the soils to be susceptible to erosion due to a clear textural change between top- and subsoils. While topsoils were predominantly sandy, subsoils had high clay contents. This textural change was specifically distinct in soils that had developed on grus slope deposits, a fact that has also been described by Esu and Ojanuga (1985), Fagbami (1981) and Wall (1979). Furthermore, pediment slopes of up to 4° may exacerbate such erosion risks. Soils that had developed on pediments were relatively shallow (see Table 3.16); in such cases, root development possibilities were assumed to be suboptimal.

Table 3.17 Background particle-size distribution of soils developed on different West African parent materials.

[Based on (1) Jones & Wild (1975); (2) Junge & Skowronek (2007); (3) Fagbami et al. (1985a)]

Parent material	Sand	Silt	Clay	Ref.
	(%)			
Grus slope deposits	40.7	32.0	27.3	(1)
Pisolite slope deposits	75.9	17.5	6.6	(2)
River deposits (clayey)	8.0	16.0	76.0	(1)
River deposits (sandy)	79.5	15.4	5.1	(3)
Migmatite-gneiss complex slope deposits	36.3	33.4	30.3	(1)
Metasediment (schist) slope deposits	1.8	34.9	54.3	(1)
Sandstone (Continental Terminal) slope deposits	50.3	29.6	19.1	(1)
Basalt slope deposits	19.8	47.3	32.9	(1)

(Sand: 2000-63 µm; Silt: 63-2 µm; Clay: < 2 µm; Ref. reference)

In summary, the soils in the Kaduna study area had sandy topsoils and clayey (argilic) subsoils, which made the subsoils susceptible to erosion, especially in high-slope areas. With such physical characteristics, the soils in the Kaduna study area are comparable to other soils known from the northern Nigerian literature.

3.4.4 Clay mineralogy

Clay minerals, which are common weathering products of primary silicates, have a varying ability to attract or repulse charge ions to or from their surfaces and are thus an important factor in assessing the potential soil fertility (Moore & Reynolds, 1997; Scheffer & Schachtschabel, 2002). In tropical soils, the most typical clay mineral is kaolinite ($Al_2Si_2O_5(OH)_4$), a low-activity, 1:1 clay mineral that has a very small surface area and a small capacity to host cations in addition to Al and SiO_2 (Alloway, 2013; Garrett, 2013; Pagel, 1981).

In the soils of the Kaduna study area, kaolinite was the dominant clay mineral. The mean contents of kaolinite ranged between 50% and 70% by volume. The highest contents were found in the soils that had developed on pisolite slope deposits. Goethite ($FeO(OH)$), an iron-bearing oxide mineral (Moore & Reynolds, 1997), was present in the soil clay fractions, averaging 20%. Illite ($(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$), which is a weathering product of feldspar (Moore & Reynolds, 1997), was present in the clay fractions by greater than 4.9% of the volume. Stable quartz (SiO_2) was found in most soils, while contents were always greater than 10%. Less-stable K-feldspars ($KAlSi_3O_8$) were found only in trace concentrations. Gibbsite ($Al(OH)_3$) and albite ($NaAlSi_3O_8$) were very rarely distributed and were only found in the clay fractions of some soils, independent of slope position and soil type (see Table 3.18).

Compared to the soils in the LR village Panzato, the soils in the HR village Kaso had higher contents of kaolinite, while soils in the LR village had significantly higher contents of illite (see Table 3.18). Since clay minerals of the illite group have a greater capacity to adsorb cations (Scheffer & Schachtschabel, 2002), the soils in the LR village were assumed to have a higher CECpot than the soils in the HR village.

Table 3.18 Mineralogy of soil clay fractions in the Kaduna study area.

Detailed soil-type-specific data are given in Appendix B.

Study site	Parent material	n	Kln	Gt	Ill	Qtz	K-Fs	Others
			(%)					
HR village	Grus slope deposits	-	nd	nd	nd	nd	nd	nd
	Pisolite slope deposits	11	69.6	19.2	trace	7.4	trace	Gbs, Ab
	River deposits (clayey)	5	61.8	25.8	trace	9.6	trace	Gbs
HR village mean			65.7	22.5	trace	8.5	trace	Gbs, Ab
LR village	Grus slope deposits	17	62.8	19.4	11.1	6.9	trace	Gbs
	Pisolite slope deposits	3	52.3	22.0	14.4	8.4	trace	Gbs
	River deposits (sandy)	-	nd	nd	nd	nd	nd	nd
LR village mean			57.6	20.7	12.8	7.7	trace	Gbs

[Ab: albite; Fs: feldspar; Gbs: gibbsite; Gt: goethite; Ill: illite; Kln: kaolinite; Qtz: quartz; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

Compared to the average clay mineralogical makeup of soils in the northern guinea savanna, the clay mineral concentrations in the Kaduna study area were relatively small, as indicated by the spectra. Clay minerals, such as vermiculite ($(Mg,Fe,Al)_3(Al,Si)_4O_{10}(OH)_2$ $4H_2O$), chlorite ($(Mg,Fe)_3(Si,Al)_4O_{10}$) and Ca-Na-feldspars ($(Ca,Na)Si_2O_8$), which have been reported from other areas in northern Nigeria (Møberg & Esu, 1991; Ojanuga, 1979), were not identified (compare Tables 3.18 and 3.19). Vermiculite, chlorite and Ca-Na-feldspars are minerals which are typically brought in by harmattan dusts or are found in perennial water-logged soils (Wilke et al., 1991; Lyngsie et al.,2011). The reason for the lack of vermiculite, chlorite and Ca-Na-feldspars in the study area soils is unknown.

Apart from vermiculite, chlorite and Ca-Na-feldspars, all the other clay minerals in the soils of the Kaduna study area were typical for tropical crystalline basement areas (Abe et al., 2006; Junge & Skowronek, 2007; Møberg & Esu, 1991): easily weatherable minerals, such as pyroxene, hornblende and mica ($(K,Na,Ca)_2(Al,Mg,Fe)_{4\text{-}6}(Si,Al,Fe)_8O_{20}(OH,F)_2$), are already absent, while kaolinite, produced by the chemical weathering of aluminium silicate minerals, such as feldspar and biotite, dominates (Agbenin & Yakubu, 2006; Rebertus et al., 1986). Only in areas where basalt is the underlying bedrock is the clay mineralogical makeup clearly different than in areas underlain by granites (Møberg & Esu, 1991) (see Table 3.19).

Table 3.19 Background mineralogy of soil clay fractions developed on different Nigerian parent materials.

[Based on (1) Møberg & Esu (1991); (2) Junge & Skowronek (2007); (3) Abe et al. (2006)]

Parent material	Kln	Gt	Ill	Qtz	K-Fs	Others	Ref.
	(%)						
Grus slope deposits	60.0	10.0	10.0	6.0	trace	Vrm, Chl	(1)
Pisolite slope deposits	75.0	trace	30.0	-	-	-	(2)
River deposits	50.0	trace	10.0	26.0	trace	-	(3)
Migmatite-gneiss complex slope deposits	68.0	8.0	8.0	6.0	trace	Vrm, Chl	(1)
Metasediment (schist) slope deposits	64.0	22.0	trace	trace	trace	-	(1)
Basalt slope deposits	11.0	trace	12.0	6.0	trace	Sme	(1)

(Chl: chlorite; Gt: goethite; Ill: illite; K-Fs: K-feldspar; Kln: kaolinite; Qtz: quartz; Sme: smectite; Vrm: vermiculite; Ref. reference)

In summary, the soil clay fractions of the Kaduna study had low contents of harmattan dust-derived clay minerals but contained minerals that are typical for areas of the northern guinea savanna, underlain by granites. The soil fertility should be generally low, due to a clear dominance of kaolinite. Therefore, the kaolinite contents were higher in the HR-village soils than in the LR-village soils.

3.4.5 pH and organic carbon

In the estimation of soil health, pH values and the concentrations of organic carbon (OC) are essential determinants as they influence the availability of macronutrients, micronutrients as well as trace elements in soils (Pagel, 1981; Scheffer & Schachtschabel, 2002). In such a way, low pH values stimulate element availabilities, while high concentrations of OC typically cause the retention of macronutrients, micronutrients as well as PTEs (Alloway, 2013; Kabata-Pendias & Mukherjee, 2007).

In the Kaduna study area, the soils were acidic, with pH values ranging between 4 and 5 on average. Only in the soils developed on grus slope deposits were pH values as high as 6. The lowest pH values were found in the A horizons of the river valley soils and in the B and C horizons of soils developed on pisolite slope deposits. The median OC concentrations ranged between 0.1 and 1.4% and generally, except for the river valley soils, decreased with depth (see Table 3.20).

Table 3.20 pH values and OC concentrations of soils in the Kaduna study area.
Detailed soil-type-specific data are given in Appendix B.

Study site	Dominant parent material	Horizon	pH		OC	
			Mean ± SD	Median	Mean ± SD	Median
					(%)	
HR village	Grus slope deposits	A	5.3 ± 0.6	5.6	0.6 ± 0.2	0.7
		B	5.2 ± 0.5	5.2	0.6 ± 0.4	0.7
	Pisolite slope deposits	A	4.6 ± 0.4	4.7	1.1 ± 0.2	1.2
		B	4.2 ± 0.1	4.2	0.5 ± 0.2	0.4
		C	4.3 ± 0.5	4.1	0.4 ± 0.1	0.4
	River deposits (clayey)	A	4.4 ± 0.6	4.1	1.2 ± 1.1	0.7
		B	4.6 ± 0.3	4.7	0.7 ± 0.3	0.6
		C	4.5 ± 0.0	4.5	1.4	1.4
HR village mean			4.5 ± 0.5		0.7 ± 0.5	
LR village	Grus slope deposits	A	5.7 ± 0.3	5.7	0.9 ± 0.1	0.9
		B	4.7 ± 0.3	4.7	0.3 ± 0.2	0.2
	Pisolite slope deposits	A	5.5	5.5	0.9	0.9
		B	4.2 ± 0.1	4.2	0.4 ± 0.2	0.4
	River deposits	A	4.0 ± 0.0	4.0	0.6	0.6
		B	4.6 ± 0.4	4.6	0.3 ± 0.1	0.3
		C	5.7 ± 0.0	5.7	0.1	0.1
LR village mean			4.9 ± 0.6		0.5 ± 0.3	
Study-area mean			4.7 ± 0.6		0.6 ± 0.4	

[pH determined in KCl; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

The soils in the HR village Kaso had slightly lower pH values than the soils in the LR village Panzato (mean: 4.5 ± 0.5 vs. 4.9 ± 0.6). In contrast, the mean OC concentrations were slightly higher in the HR-village soils than in the LR-village soils (mean: 0.7 ± 0.5% vs. 0.5 ± 0.3%). With regard to the differences that were already identified between the HR-village soils and the LR-village soils in terms of parent material, soil clay minerals and erosion intensity, a pisolite and kaolinite dominance of the soils in the HR village was assumed to have caused slightly lower pH values, while the higher risk of erosion in the LR village Panzato may have caused lower OC concentrations in the soils of these two study sites.

Compared to the background levels of soils from other parts in West Africa (see Tables 3.20 and 3.21), both Kaduna study sites showed low soil pH values. These background levels, however, were determined in a 1 : 2.5 soil : water suspension (Jones & Wild, 1975; Junge & Skowronek, 2007), a method which produces pH values of around one unit higher than those measured with KCl (Landon, 1991; Vanlauwe et al., 2002), which was used for pH measurements in soils of this study (see Chapter 2.4.2). The differences between the Kaduna study area soil pH values and those found in other areas of West Africa may therefore not be that great.

When comparing the OC concentrations of the soils in the Kaduna study area to West African background levels, the OC concentrations in the study area were lower than those of typical West African soils (Jones & Wild, 1975; Junge & Skowronek, 2007) (see Tables 3.20 and 3.21). However, as OC concentrations depend on land-use type and land-use intensity and often vary on a local scale (Fordyce et al., 1996), any comparisons of areas with a similar parent material have to be considered with care. For comparison purposes, the data presented by Alloway (2013) are more useful: Agriculturally-used soils were reported to typically have OC concentrations of less than 1%, while permanent grassland soils in humid conditions tend to have greater than 10% OC in subsoils. Based on these findings, the soils of the Kaduna study area can be assessed having normal to marginal OC concentrations in the soils.

Table 3.21 Background pH values and OC concentrations of soils developed on different West African parent materials.

[Based on (1) Jones & Wild (1975); (2) Junge & Skowronek (2007)]

Parent material	pH	OC (%)	Ref.
Grus slope deposits	6.2	na	(1)
Pisolite slope deposits	5.0	1.2	(2)
River deposits (clayey)	6.4	1.5	(1)
Migmatite-gneiss complex slope deposits	5.8	1.6	(1)
Metasediment (schist) slope deposits	6.9	1.4	(1)
Sandstone (Continental Terminal) slope deposits	5.9	0.6	(1)
Basalt slope deposits	6.5	2.0	(1)

(pH determined in water solution; Ref.: reference)

To assess the overall health of the Kaduna study area soils, the pH values and OC concentrations were additionally compared to critical limits as given by Landon (1991). According to these critical limits (see Table 3.22), the pH value is critically low when the level falls below a value of 5. As this limit, however, was measured in water solution, which produces pH values a unit higher than those measured with KCl, one should consider pH values measured with H_2O of less than 4.0 to be critically low. Compared to this, the pH values measured with KCl, with values averaging 4.7 ± 0.6 in the study area soils, were still moderate.

Compared to the OC critical limit given by Landon (1991), in which soils are considered critically low in OC when concentrations fall below 0.4% (see Table 3.22), the OC concentrations in the Kaduna study area soils, with concentrations averaging 0.6 ± 0.4%, ranged from normal to slightly deficient. Only in a few subsoils were the OC concentrations lower than this critical limit (compare Tables 3.20 and 3.22). However, since plants take most of their nutrients from the A and B horizons, the low OC concentrations in the C horizons of some of the Kaduna study area soils should have no further detrimental effect on healthy crop growth.

Table 3.22 Critical pH and OC soil limits linked to limited crop health.

[Based on Landon (1991)]

pH	OC
	(%)
< 5.0	< 0.4

(pH determined in water solution)

In summary, the soils in the Kaduna study area had normal to slightly elevated pH values and contained normal to marginal OC concentrations compared to West African background levels and critical limits. The lower pH and higher OC concentrations in the HR-village soils compared to the LR-village soils were assumed to be caused by differences in parent material, clay mineralogical makeup and erosion intensity between the two study sites.

3.4.6 Potential cation-exchange capacity and base saturation

Measurements on the potential cation-exchange capacity (CECpot) are commonly made to assess the potential fertility of a soil, as this variable gives an idea of the maximum quantity of total cations that a soil is capable of holding. Base saturation (BS), which is the proportion of CECpot accounted by exchangeable bases (Ca, Mg, K and Na), is a powerful indicator of soil fertility (Landon, 1991). Low CECpot and BS is an indicator of low soil fertility (Scheffer & Schachtschabel, 2002; Young, 1976).

The soils of the Kaduna study area showed a mean CECpot of 9.4 ± 3.0 cmol kg^{-1} and a mean BS of 39.1 ± 16.0%. Only one horizon of one soil profile showed the BS to be significantly lower than 6.3%, which also caused the BS standard deviation (SD) to be relatively high (see Table 3.23). In all the soils, the BS clearly decreased with depth, a phenomenon that is known to be caused by the so-called pumping effect, which is a return of cations to the soil surface through crop and vegetation root transport (Jones & Wild, 1975). Only in the river valley soils did the BS vary between the different horizons, while no clear pattern of distribution was identified. The CECpot was more or less similar in all the soils, independent of the parent material. In contrast, the BS was highest in soils developed on grus slope deposits > river deposits > pisolite slope deposits (see Table 3.23).

Comparisons between the HR and LR villages showed the CECpot to be higher in the soils of the HR village Kaso (mean: 10.7 ± 2.4 vs. 7.7 ± 3.0 cmol kg^{-1}). Generally, a high CECpot depends on various factors, including low pH values, high OC concentrations and high contents of high-activity clay minerals (Landon, 1991). As the pH values and the OC concentrations were higher in the HR-village soils than in the LR-village soils (see Chapter 3.4.5), these differences may explain the differences in the CECpot in the soils of the two study sites.

With regard to BS, the soils of the LR village Panzato seemed to be well equipped with exchangeable cations. The mean BS in the LR-village soils was 46.9 ± 14.2%, while in the HR-village soils, the mean BS was only 33.1 ± 14.8%. This difference was assumed to be caused by differences in parent material. While the soils in the LR village had mostly developed on grus slope deposits, which provide considerable concentrations of cations to soils, the soils in the HR village had developed on pisolite slope deposits, which contain lower concentrations of cations (see Table 3.24). Grus dominance in the LR-village soils was therefore assumed to be one important factor leading to the higher BS in the soils of this study site. According to Landon (1991), a CECpot below 10 cmol kg^{-1} is an indicator that kaolinite is the dominant clay mineral in a given soil. Such a low level is typical for most soils in the tropics and was also found in the soils of the Kaduna study area. Nwoke et al. (2004), who analysed the soil fertility of soils in Kasuan Magani, a village which is part of the study area (see Figure 3.7), found the CECpot of soils in this area to range between 4.0 and 27.0 cmol kg^{-1}. According to Delaure (1998), the CECpot of soils in the northern guinea savanna typically range between 10 to 35 cmol kg^{-1}. Similar levels have been reported by Jones and Wild (1975). Compared to these background levels, the results of this study were, with an overall mean CECpot of 9.4 ± 3.0 cmol kg^{-1}, low. A particularly high or low CEC is found only in areas dominated by sandstone, basalt or schist slope deposits, respectively (see Table 3.24).

Table 3.23 CECpot and BS of soils in the Kaduna study area.

Detailed soil-type-specific data are given in Appendix B.

Study site	Dominant parent material	Horizon	CECpot		BS	
			Mean ± SD	Median	Mean ± SD	Median
			(cmol kg^{-1})		(%)	
HR village	Grus slope deposits	A	10.6 ± 1.7	9.8	57.5 ± 1.6	57.4
		B	11.6 ± 1.5	12.4	51.9 ± 12.7	56.0
	Pisolite slope deposits	A	11.4 ± 3.7	9.7	31.4 ± 10.4	38.3
		B	10.0 ± 1.4	9.7	32.8 ± 9.3	31.6
		C	11.0 ± 2.3	9.6	22.8 ± 6.4	27.5
	River deposits	A	11.3 ± 3.1	11.3	30.2 ± 5.6	30.2
		B	10.9 ± 2.1	12.0	9.8 ± 7.0	6.3
		C	7.8	7.8	33.2	33.2
HR village mean			10.7 ± 2.4		33.1 ± 14.8	
LR village	Grus slope deposits	A	7.7 ± 3.5	7.4	58.7 ± 12.2	60.7
		B	8.9 ± 3.2	8.3	43.4 ± 12.1	42.2
	Pisolite slope deposits	A	5.5	5.5	54.5	54.5
		B	7.2 ± 1.3	7.2	33.0 ± 7.5	33.0
	River deposits	A	6.8	6.8	26.9	26.9
		B	5.8 ± 0.4	5.8	43.3 ± 10.3	43.3
		C	2.2	2.2	77.4	77.4
LR village mean			7.7 ± 3.0		46.9 ± 14.2	
Study-area mean			9.4 ± 3.0		39.1 ± 16.0	

[CECpot and BS extracted with $BaCl_2$; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

Similarly, an overall mean BS of 39.1 ± 16.0% in the soils of the Kaduna study area was moderate compared to West African background levels, which typically range between 22.0 to 41.4%. A markedly high BS of >50% is to be expected in West African soils only where slope deposits are dominated by weathering products of migmatite-gneiss complex, metasediment or basalt. A lower BS of <40% is found only in areas where pisolite or sandstone slope deposits are the major parent materials (Ameyan, 1985; Jaiyeoba, 1995; Valette & Ibanga, 1984) (see Table 3.24).

However, these West African CECpot and BS background levels (see Table 3.24) were measured after ammonium acetate ($NH_4C_2H_3O_2$) extraction only. As ammonium acetate generally extracts higher macronutrient concentrations than measurements after $BaCl_2$ extraction (Landon, 1991), the ammonium acetate-measured West African background levels were expected to be generally higher than the results of this study. The exact difference that these two extractants produce can, however, not be generalized or expressed in a specific unit, as it depends on many different physicochemical soil characteristics (Ciesielksi & Sterckeman, 1997).

Table 3.24 Background CECpot and BS of soils developed on different West African parent materials.

[CECpot based Jones & Wild (1975); BS based on Ameyan (1985); Jaiyeoba (1995); Valette & Ibanga (1984)]

Parent material	CECpot	BS
	(cmol kg^{-1})	(%)
Grus slope deposits	12.3	46.0
Pisolite slope deposits	11.2	22.0
River deposits (clayey)	19.9	41.4
Migmatite-gneiss complex slope deposits	13.5	54.8
Metasediment (schist) slope deposits	31.6	53.4
Sandstone (Continental Terminal) slope deposits	4.6	40.8
Basalt slope deposits	33.5	57.9

(CECpot and BS extracted with ammonium acetate)

Compared to critical limits, the soils of the study area were found to have a normal CECpot and BS. Landon (1991) stated that CECpot is critically low in tropical soils only when it is less than 5 cmol kg^{-1} and that the BS is low when it is less than 20% (see Table 3.25). These critical limits are clearly lower than the results of this study, which showed the mean CECpot in the Kaduna study area's soils to be 9.4 ± 3.0 cmol kg^{-1} and the mean BS to be 39.1 ± 16.0% (see Table 3.23). As the results of this study were based on measurements after a weaker $BaCl_2$ extraction, the difference between the study results and the critical limits, which were based on extraction with ammonium acetate, may become even more distinct. The findings therefore suggest that the CECpot and BS were sufficiently high in the soils of the Kaduna study area to guarantee healthy crop production.

Table 3.25 Critical CECpot and BS soil limits linked to macronutrient and micronutrient deficiency in food crops.

[Based on Landon (1991)]

CECpot	BS
(cmol kg^{-1})	(%)
< 5.0	< 20.0

(CECpot and BS extracted with ammonium acetate)

To make the differences between the study results, West African background levels and critical limits even more visible, box plot diagrams, including the CECpot and BS of the soils in the Kaduna study area, West African background levels and critical limits are depicted in Figure 3.7.

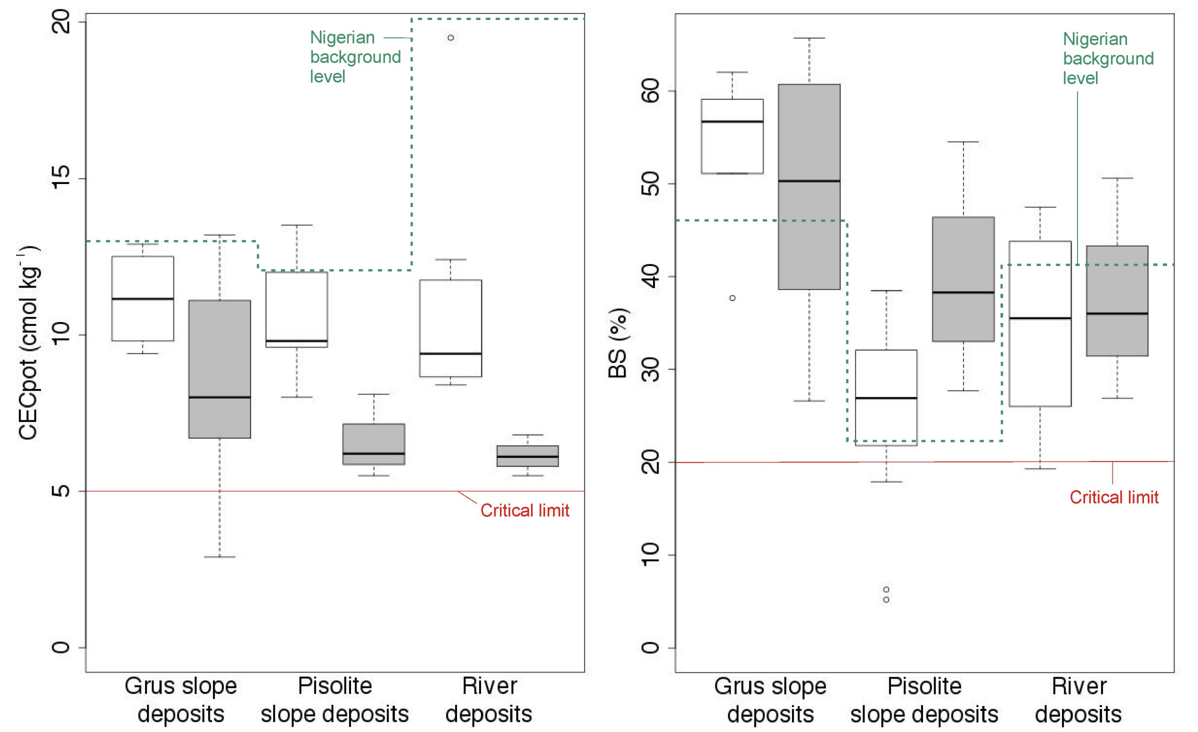

Figure 3.7 CECpot and BS of soils developed on different parent materials in the Kaduna study area compared to background levels and critical limits.

[White bars represent CDR-high-risk (HR) village Kaso: CDR prevalence rate > 5%; grey bars represent CDR-low-risk (LR) village Panzato: CDR prevalence rate ≤ 5%; dashed green lines represent Nigerian background levels (as given by Ameyan, 1985; Jaiyeoba, 1995; Jones & Wild, 1975; Valette & Ibanga, 1984); solid red lines represent critical limits (as given by Landon, 1991)]

In summary, the soils of the Kaduna study area had a normal CECpot and BS compared to Nigerian background levels and critical limits (see Figure 3.7). A detrimental effect of these two parameters, causing macronutrient and micronutrient deficiencies in the soil-plant pathway therefore was estimated to be unlikely.

3.4.7 Macronutrients

It is a well known fact that most soils in the West African savanna contain inherently low concentrations of macronutrients, such as Ca, Mg, K and P, causing major constraints in crop production (Nwoke et al., 2004; Sillanpää, 1982) and human health (Lal, 2009; Whitehead, 2000). Animal experiments have shown that the regular consumption of plant food deficient in P affects the bone formation in salmon and rats (Fjelldal et al., 2012; Rader et al., 1979) and causes hypophosphatemic rickets in children (Calvo & Carpenter, 2003). Moreover, a one-sided diet consisting of crop products inherently low in Ca contents is known to affect bone health, both in animals and humans (Prentice & Bates, 1994; Walker et al., 1996). Although the effects of Mg and K on bone health are still unknown, macronutrient deficiencies in the soil-plant-human pathway have already been linked to Mseleni joint disease in South Africa (Ceruti et al., 2003; Pooley, 1997). With this background, the concentrations of Ca, Mg, K and P in the soils of the Kaduna study area were of interest in this doctoral thesis.

Table 3.26 Plant-available Ca, Mg and K concentrations of soils in the Kaduna study area.

Detailed soil-type-specific data are given in Appendix B.

Study site	Dominant parent material	Horizon	Plant-available					
			Ca		Mg		K	
			Mean ± SD	Median	Mean ± SD	Median	Mean ± SD	Median
			(cmol kg^{-1})					
HR village	Grus slope deposits	A	4.8 ± 0.2	4.7	0.7 ± 0.1	0.7	0.3 ± 0.2	0.3
		B	4.8 ± 1.0	5.0	1.0 ± 0.2	1.1	0.2 ± 0.1	0.1
	Pisolite slope deposits	A	3.0 ± 1.8	3.3	0.7 ± 0.2	0.8	0.1 ± 0.0	0.1
		B	2.6 ± 1.1	2.2	0.6 ± 0.2	0.6	0.1 ± 0.1	0.1
		C	1.9 ± 0.3	1.9	0.7 ± 0.2	0.7	0.1 ± 0.1	0.1
	River deposits (clayey)	A	2.5 ± 0.1	2.5	0.7 ± 0.1	0.7	0.2 ± 0.1	0.2
		B	0.9 ± 0.5	0.9	0.1 ± 0.1	0.1	0.1 ± 0.1	0.0
		C	1.4	1.4	1.1	1.1	0.1	0.1
HR village mean			2.8 ± 1.6		0.7 ± 0.3		0.1 ± 0.1	
LR village	Grus slope deposits	A	2.2 ± 0.9	2.8	0.6 ± 0.4	0.5	0.2 ± 0.1	0.2
		B	3.1 ± 1.2	3.2	0.9 ± 0.5	0.9	0.2 ± 0.1	0.3
	Pisolite slope deposits	A	2.1	2.1	0.5	0.5	0.2	0.2
		B	2.0 ± 0.8	2.0	0.4 ± 0.2	0.4	0.1 ± 0.0	0.1
	River deposits (sandy)	A	1.5	1.5	0.2	0.2	0.1	0.1
		B	2.1 ± 0.6	2.1	0.4 ± 0.1	0.4	0.1 ± 0.0	0.1
		C	1.4	1.4	0.2	0.2	0.0	0.0
LR village mean			2.6 ± 1.1		0.7 ± 0.4		0.2 ± 0.1	
Study-area mean			2.7 ± 1.4		0.7 ± 0.4		0.1 ± 0.1	

[plant-available Ca, Mg and K extracted with BaCl$_2$; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

In the soils of the Kaduna study area, plant-available nutrients were present in the order Ca > Mg > K > P with mean Ca, Mg, K and P concentrations of 2.7 ± 1.4 cmol kg^{-1}, 0.7 ± 0.4 cmol kg^{-1}, 0.1 ± 0.1 cmol kg^{-1} and 0.005 ± 0.1 cmol kg^{-1} (= 2.3 ± 4.1 mg kg^{-1}), respectively. The mean Ca, Mg and K concentrations were highest in soils that had developed on grus slope deposits, while the concentration of Ca, Mg, K and P always increased with depth. In soils that had developed on pisolite slope deposits and river deposits, the Ca, Mg and K concentrations were highest in the topsoils. The mean P concentrations were more or less similar in all the soils, but were still often highest in the topsoils (see Tables 3.26 and 3.27).

The comparisons between the HR-village soils and the LR-village soils showed soil plant-available Ca concentrations in the HR-village soils to be higher on average than in the LR-village soils (mean: 2.8 ± 1.6 vs. 2.6 ± 1.1 cmol kg^{-1}). The same was found for P concentrations, which were again higher in the HR-village soils than in the LR-village soils (mean:

3.2 ± 5.2 vs. 1.2 ± 1.4 mg kg^{-1}). However, the standard deviation (SD) was very high for the P concentrations in the HR-village soils, which may make this distinction less strong than expected at first sight (see Tables 3.26 and 3.27). The elevated median P concentrations in the topsoils of all the analysed soils were assumed to be caused by P-fertilizer inputs (see Chapter 3.3). The plant-available concentrations of Mg were similar in the soils of the HR village and the soils of the LR village (0.7 ± 0.3 vs. 0.7 ± 0.4 cmol kg^{-1}) (see Tables 3.26 and 3.27). The soil K concentrations were slightly lower in the HR-village soils than in the LR-village soils (0.1 ± 0.1 vs. 0.2 ± 0.1 cmol kg^{-1}) (see Tables 3.26 and 3.27), which was assumed to be caused by the dominance of K-bearing, biotite-rich grus slope deposit parent material in the LR-village soils (see Chapter 3.2).

Table 3.27 Plant-available P concentrations of soils in the Kaduna study area.
Detailed soil-type-specific data are given in Appendix B.

Study site	Dominant parent material	Horizon	Plant-available P Mean ± SD (mg kg^{-1})	Plant-available P Median (mg kg^{-1})
HR village	Grus slope deposits	A	6.0 ± 3.5	8.0
		B	2.0 ± 1.7	1.0
	Pisolite slope deposits	A	2.3 ± 1.2	2.0
		B	1.4 ± 0.9	2.0
		C	8.8 ± 10.8	2.5
	River deposits (clayey)	A	2.0 ± 1.4	2.0
		B	2.0 ± 2.6	1.0
		C	1.0	1.0
HR village mean			3.2 ± 5.2	
LR village	Grus slope deposits	A	2.2 ± 0.9	2.0
		B	0.4 ± 0.5	0.0
	Pisolite slope deposits	A	4.0	4.0
		B	1.5 ± 0.7	1.5
	River deposits (sandy)	A	0.5	0.5
		B	0.5	0.5
		C	0.0	0.0
LR village mean			1.2 ± 1.4	
Study-area mean			2.3 ± 4.1	

[plant-available P extracted with Ca acetate lactate (CAL); HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

Assuming that the CDR in the Kaduna area is caused by macronutrient deficiencies, one may expect plant-available macronutrient concentrations, especially Ca and P, to be lower in the HR-village soils than in the LR-village soils, according to the differences in the CDR prevalence rates. However, the concentrations of Ca and P tended to always be higher in the HR-village soils than in the LR-village soils, which does not support the research hypothesis and questions the link between the macronutrient concentrations of soils and the CDR in humans. Furthermore, this result stands in contrast to findings of the author of this doctoral thesis in the context of her Master's thesis (Hartmann, unpublished, 2009), but may be explained by the fact that the Ca concentrations measured in the rural Kaduna area's soils in the context of the Master thesis (*Diplomarbeit*) were measured only in total but not plant-available concentrations, which may have biased the Master thesis' research results.

Comparisons of the study results to West African background levels showed the soils in the Kaduna study area to contain on average lower Ca, Mg and K concentrations than typical soils in West Africa (compare Tables 3.26 and 3.28). This difference, however, may be caused by the use of different extractants. According to Ciesielksi and Sterckeman (1997), the extraction using $BaCl_2$, which was the extractant used in the current study's analyses, produces significantly lower macronutrient concentrations than the ammonium acetate extractant, which was used for the measurement of the West African background levels (Junge & Skowronek, 2007; Landon, 1991) (see Table 3.28).

Table 3.28 Background Ca, Mg and K concentration of soils developed on different West African parent materials.

[Based on (1) Jones & Wild (1975); (2) Junge & Skowronek (2007)]

Parent material	Plant-available				Ref.
	Ca	Mg	K	P	
	(cmol kg^{-1})			(mg kg^{-1})	
Grus slope deposits	4.8	1.4	0.3	na	(1)
Pisolite slope deposits	1.5	1.1	0.1	na	(2)
River deposits (clayey)	6.6	1.6	0.4	na	(2)
Migmatite-gneiss complex slope deposits	8.3	2.7	0.3	na	(1)
Metasediment (schist) slope deposits	19.7	11.4	0.3	na	(1)
Sandstone (Continental Terminal) slope deposits	1.9	1.1	0.1	na	(1)
Basalt slope deposits	6.9	8.9	0.1	na	(1)

(Plant-available Ca, Mg and K extracted with ammonium acetate; plant-available P extracted with Olsen method; na: not available; Ref.: reference)

However, when comparing the $BaCl_2$-extractable, plant-available macronutrient concentrations of this study, which showed mean plant-available Ca, Mg, K and P concentrations of 2.7 cmol kg^{-1}, 0.7 cmol kg^{-1}, 0.1 cmol kg^{-1} and 2.3 mg kg^{-1}, respectively, to background levels measured with the same extractant, the macronutrient concentrations of the soils in the study area are found to be quite typical for the northern guinea savanna. Fagbami et al. (1985a), who analysed the background macronutrient concentrations of soils that had developed on basement-rock slope deposits in Nigeria, found $BaCl_2$-extractable, plant-available Ca and Mg concentrations to range between 0.7 to 5.8 cmol kg^{-1} and 0.1 to 7.1 cmol kg^{-1}, respectively. Raji et al. (2011), who analysed soils on basement-granite and basement-gneiss slope deposits near Zaria City, northern Nigeria, found $BaCl_2$-extractable, plant-available Ca, Mg and K concentrations in the uppermost 50 cm of soils to be around 2.0, 1.0 and 0.3 cmol kg^{-1}, respectively. Considerably higher or lower Ca, Mg and K concentrations were found only in areas underlain by schist and basalt or ferricretes and sandstone, respectively, a fact that has already been discussed in Chapter 3.1. Finding information on Nigerian P soil background levels including references to parent material, was astonishingly a bit more difficult. A good background level was found in the study of Pypers et al. (2006), who analysed the P concentrations of soils in Kasuan Magani, which is a small village in the east of the Kaduna study area (see Figure 3.7). Accordingly, the P concentrations in Kasuan Magani are commonly 2.1 mg kg^{-1} in the upper 20 cm of the soils. This concentration is slightly lower than the Kaduna-study-area P mean of 2.3 ± 4.1 mg kg^{-1} (see Table 3.27). However, as the P concentrations given by Pypers et al. (2006) were measured by the Olsen method, which extracts lower concentrations of P in non calcareous tropical soils than the Ca acetate lactate (CAL) extraction used in this study (Mamo et al., 2002), this slight difference may just be due to differences in laboratory method. Isichei and Muoghalu (1992), who analysed soils in basement areas of the northern guinea savanna, found typical P concentrations to be around 3.7 mg kg^{-1}. The authors used the Bray-1 method, which produces P concentrations that are around one unit higher than those measured by the Olsen method (Ayodele & Agboola, 1981). Odunze et al. (2002) found Bray-1 P concentrations in the soils around Zaria, which is a city 80 km north of the study area and which is likewise underlain by Older Granites, to be as high as 3.9 mg kg^{-1}. A concentration that is, considering the differences in the extraction, again comparable to the findings in this study.

The critical limits for soil macronutrients can vary considerably with crop variety and level of production (Jones & Wild, 1975). Njoku et al. (1987), for instance, found maize plants in the coastal sand areas of south-east Nigeria to be severely affected by Ca deficiency due to plant-available Ca soil concentrations below 0.7 cmol kg^{-1}. For groundnut cultivation, Meredith (1965) reported Ca deficiencies in Nigerian soils to occur at Ca concentrations of less than 0.8 cmol kg^{-1}. Ritchey et al. (1982) found Ferralsols in Brazil to cause Ca deficiency in crops only when soil Ca concentrations are below 0.2 cmol kg^{-1} and Landon (1991) reports that a Ca deficiency in maize occurs at Ca concentrations in soil of less than 0.7 cmol kg^{-1}. As maize was the main food crop in the Kaduna study area, the critical limit given by Landon (1991) was taken for further comparisons (see Table 3.29).

Table 3.29 Critical Ca, Mg, K and P soil limits linked to deficiency symptoms in food crops.

[Based on Landon (1991)]

Plant-available			
Ca	**Mg**	**K**	**P**
(cmol kg^{-1})			**(mg kg^{-1})**
< 0.7	< 0.5	< 0.2	< 5.0

(Plant-available Ca, Mg and K extracted with ammonium acetate; plant-available P determined with the Olsen method)

Compared to these critical limits, the macronutrient concentrations of the soils in the Kaduna study area were on average low in P (< 5.0 vs. 2.3 ± 4.1 mg kg^{-1}), while the K (< 0.2 vs. 0.1 ± 0.1 mg kg^{-1}) and the Mg concentrations (< 0.5 vs. 0.7 ± 0.4 mg kg^{-1}) were marginal and the Ca concentrations (< 0.7 vs. 2.7 ± 1.4 mg kg^{-1}) were sufficient for healthy crop growth (compare Tables 3.26, 3.27 and 3.29).

However, the critical Ca, Mg and K limits as given in Table 3.29 were measured after ammonium acetate extraction, which produces higher concentrations as those measured after $BaCl_2$ extraction (Ciesielksi & Sterckeman, 1997). Furthermore, the P critical limits were measured by the Olsen method (see Table 3.29), which extracts lower P concentrations than the CAL extraction (Mamo et al., 2002), which was the extraction for the P analyses in this thesis study. This means that the K and Mg concentrations of the soils in the study area are not marginal but sufficient and that the Ca concentrations are more than adequate in the soils of the Kaduna study area. However, according to this, the P soil concentrations are, in all probability, too low for healthy crop production in the Kaduna study area.

This result is in line with results of Esu and Ojanuga (1985), who analysed pediment soils near Kaduna and found plant-available Ca, Mg and K concentrations of soils to be moderate to high, identifying only P to be too low. Very low P concentrations of soils in the northern guinea savanna have also been found by other authors (Nwoke et al., 2004; Sanginga et al., 1995; Vanlauwe et al., 2002). Jones and Wild (1975) and Mokwunye (1979) even stated that P is one of the most limiting nutrients in West African savanna soils in general. However, to be certain that P deficiency is a limiting factor in the soils of the Kaduna study area, pot experiments under real farming and ecological conditions would be necessary (Nabhan, 2000b).

Although P deficiency in the soil-plant-human pathway is known to affect vertebrate bone health (Fjelldal et al., 2012), P deficiency in nutrition causes only hypophosphatemic rickets, which is a completely different type of rickets than CDR (Calvo & Carpenter, 2003). Animal experiments, for instance, have shown that rats develop decreased PTH and increased 1.25$(OH)_2D$ levels in serum under a P-deficient diet (Rader et al., 1979), which is a haemogram that is completely different to that of CDR, where children typically show increased PTH and decreased 1.25$(OH)_2D$ levels (Emmert, 2009; Thacher et al., 2006). Moreover, the fact that P deficiency in soils is widespread in African soils and is not limited to CDR areas underpins the assumption that the P deficiency of the soils in the Kaduna study area is, in all probability, not predisposing to CDR.

Table 3.30 Background Ca, Mg and K concentration of soils in areas with Mseleni joint disease in South Africa.

[Based on Pooley (1999; 1997)]

Plant-available			
Ca	**Mg**	**K**	**P**
(cmol kg^{-1})			**(mg kg^{-1})**
< 0.3	< 0.2	< 0.2	< 1.9

(Plant-available Ca, Mg, K and P extracted with KCl)

Compared to macronutrient concentrations in the soils of the Mseleni-joint-disease areas in South Africa (Ceruti et al., 2003), the soils in the Kaduna study area contained significantly higher macronutrient concentrations (compare Tables 3.26, 3.27 and 3.30). However, the Maputaland macronutrient soil concentrations were measured after KCl extraction, a solvent which is less powerful than $BaCl_2$ (Juo et al., 1976). Although the exact unit of difference that these two extractants produce is unknown, Pooley (1997) states that macronutrients are clearly deficient in Maputaland. The Maputaland macronutrient concentrations were therefore assumed to be lower than the critical limits (see Table 3.29) and thus should have also been lower than the macronutrient concentrations of the soils near Kaduna City.

In summary, the macronutrient concentrations of the soils in the Kaduna study area decreased in the order Ca > Mg > K > P. The Ca concentrations were higher in the HR-village soils than in the LR-village soils. In contrast, the LR-village soils showed higher K concentrations than the HR-village soils, which was assumed to be caused by the dominance of K-bearing, biotite-rich grus slope deposit parent material in the LR-village soils. Mg was found to be similarly distributed in both study sites. Compared to West African background levels, the macronutrient concentrations of the soils in the Kaduna study area were within normal ranges. Compared to the critical limits, the Ca, Mg and K concentrations were identified to be sufficient in the soils of the Kaduna study area, while the P concentration was significantly low, which is typical for soils of the northern guinea savanna (see Figure 3.8). However, as P deficiency in nutrition is known to cause hypophosphatemic rickets and not CDR, a link between P deficiency in soils and CDR in humans was considered unlikely for the Kaduna study area.

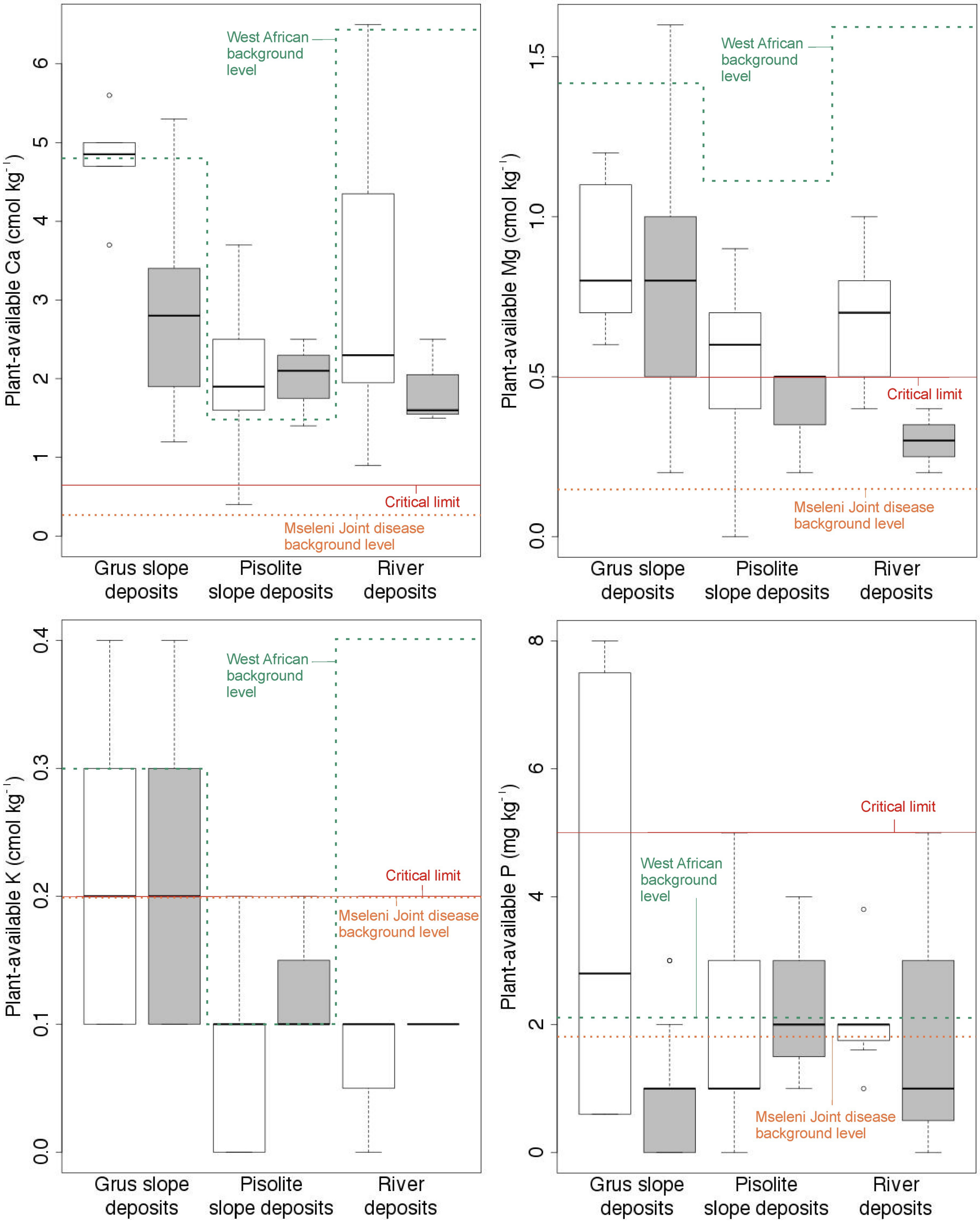

Figure 3.8 Plant-available Ca, Mg, K and P concentrations of soils developed on different parent materials in the Kaduna study area compared to background levels and critical limits.

[White bars represent CDR-high-risk (HR) village Kaso: CDR prevalence rate > 5%; grey bars represent CDR-low-risk (LR) village Panzato: CDR prevalence rate ≤ 5%; dashed green lines represent background levels (as given by Fagbami et al., 1985a; Jones & Wild, 1975; Junge & Skowronek, 2007; Pypers et al., 2006); dotted orange lines represent background levels in areas with Mseleni joint disease (as given by Pooley (1999; 1997); solid red lines represent critical limits (as given by Landon, 1991)].

3.4.8 Micronutrients

Micronutrient deficiency in soils is known to limit the healthy development of crop plants and animals (Schulin et al., 2010) and to potentially affect human bone health (Abrahams, 2002; Combs, 2013; Markert et al., 2000; Steinnes, 2009; 2011; Whitehead, 2000). Cu deficiency in soil-plant systems, for instance, which is a widespread phenomenon in many African countries (Sillanpää, 1982), is known to cause skeletal deformities in animals and humans (Lowe et al., 2002). According to Sann et al. (1978), Cu deficiency is typically found in the serum of CDR children. Analyses of the Cu and Zn concentrations in the grazing lands of rachitic camels in China showed the soils to be clearly deficient in these essential trace elements (Liu, 2005). Zn deficiency, which is known to cause bone-growth retardation and bone-mass reduction in animals and children (Eberle et al., 1999; Lowe et al., 2002), was also found in the soils of Mseleni-joint-disease areas (Pooley, 1997). According to Alloway (2009) and Kanwar and Youngdahl (1985), Zn deficiency is widespread in many tropical countries and is most likely to occur in sandy soils (Munkholm et al., 1993) and in intensively cultivated areas, especially where soils have developed on granitoid bedrock (Katyal & Vlek, 1985; Tagwira et al., 1993). In addition, low Se contents in nutrition are known to cause bone-mineral-density reduction in rats (Sasaki et al., 1994) and have been associated with cartilage changes in humans (Moreno-Reyes et al, 2001). Low Se concentrations in the environment of China are known to have caused Kashin-Beck-disease bone deformities (Fordyce, 2013; Fordyce et al., 2000; Johnson et al., 2010; 2000; Zhang et al, 2011). As Se concentrations are generally low in granitoid areas (Fordyce, 2013), Se deficiency was presumed to also be found in the soils of the Kaduna study area. Against this background, the concentrations of Cu, Zn and Se in the soils of the Kaduna study area were of interest in this doctoral thesis.

Analyses of total Cu, Zn and Se concentrations in the soils of the Kaduna study area showed the elements to be found in the order Zn > Cu > Se, while the mean total Zn, Cu and Se concentrations in the soils of the Kaduna study area were 24.2 ± 22.4 mg kg^{-1}, 12.4 ± 5.9 mg kg^{-1} and 0.7 ± 0.7 mg kg^{-1}, respectively (see Tables 3.31 and 3.32). In soils that had developed on grus slope deposits, pisolite slope deposits and river deposits, the mean Cu concentrations were 9.8 mg kg^{-1}, 6.7 mg kg^{-1} and 16.4 mg kg^{-1}, respectively. The mean Zn concentrations were 27.6 mg kg^{-1}, 20.6 mg kg^{-1} and 23.0 mg kg^{-1}, respectively. The mean Se concentrations were 0.8 mg kg^{-1}, 0.9 mg kg^{-1} and 0.3 mg kg^{-1}, respectively. Thus, Cu was highest in soils developed on river deposits, Zn was more or less equally distributed in all the soils and Se was highest in the soils that had developed on pisolite slope deposits (see Tables 3.31 and 3.32). The latter result is in line with the data of Tan et al. (2002), who found total Se concentrations in China to be particularly high in soils that had developed on iron-rich parent materials. In the Kaduna study area, the concentrations of Cu, Se and Zn increased with depth in all the soils, which indicates that these elements are rather of endogenous than of exogenous origin. According to Fagbami et al. (1985b) and Kang and Osiname (1985), increasing concentrations of micronutrients with increasing soil depth is typical for soils that have developed on basement rock-derived parent materials in northern Nigeria.

As the Cu, Se and Zn in the soils of the Kaduna study area were measured only in total concentrations, no conclusions were able to be drawn regarding the plant availability of these elements (Alloway, 2013; Fairweather-Tait et al., 2011). For a detailed geomedical assessment, however, the plant-available concentrations are necessary, to be able to estimate their impact on human bone health in the Kaduna study area (Yang et al., 2007). Due to restricted financial resources and a lack of soil sample material (see Chapter 2.1), analyses regarding the plant-available micronutrient concentrations of the soils in the

Kaduna study area were possible only for Se.

Table 3.31 Total Cu and Zn concentrations of soils in the Kaduna study area.
Detailed soil-type-specific data are given in Appendix B.

Study site	Dominant parent material	Horizon	Total			
			Cu		Zn	
			Mean ± SD	Median	Mean ± SD	Median
			(mg kg^{-1})			
HR village	Pisolite slope deposits	A	10.3 ± 0.7	10.4	13.9 ± 1.7	14.9
		B	16.0 ± 4.2	16.7	19.6 ± 5.4	19.5
		C	20.7 ± 4.9	20.9	20.6 ± 4.5	21.9
	River deposits (clayey)	A	14.9 ± 2.8	14.9	22.4 ± 0.1	22.4
		B	16.7 ± 5.4	16.7	22.2 ± 3.2	20.2
		C	19.0	19.0	29.9	29.9
HR village mean			16.2 ± 4.9		19.8 ± 5.1	
LR village	Grus slope deposits	A	8.8 ± 7.2	5.5	29.7 ± 27.1	18.4
		B	10.2 ± 3.8	11.2	26.8 ± 8.5	28.9
	Pisolite slope deposits	A	4.0	4.0	18.0	18.0
		B	8.0 ± 2.1	8.0	33.8 ± 8.5	33.8
LR village mean			9.3 ± 4.7		27.8 ± 14.5	
Study-area mean			12.4 ± 5.9		24.2 ± 22.4	

(Total Cu and Zn extracted with aqua regia; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%)

According to the results of these analyses, the water-soluble Se concentrations of the soils in the Kaduna study area were on average 0.004 ± 0.004 mg kg^{-1}, around two orders of magnitude lower than the total Se concentrations, which were 0.7 ± 0.7 mg kg^{-1} on average. Water-soluble Se concentrations were equally distributed in all the soils of the Kaduna study area, independent of parent material and study site (see Table 3.32).

Scientific information on the Cu, Zn and Se background levels in northern Nigerian soils is rare. According to Davies (1996) and Plant et al. (1996), this is mostly due to geochemical data collection in Nigeria focusing more on mineral exploration than micronutrients. Furthermore, Landon (1991) indicates that the methods needed to precisely determine the micronutrient concentrations in soils have only been developed during the last few years, in accordance with an increase in the awareness on their importance for animal and human health (Landon, 1991). In African countries, analyses on soil micronutrients were not started before the early 1950s (Kang & Osiname, 1985). This is true for most micronutrients except Se, since Se is an expensive element to analyse and advanced analytic techniques were not developed earlier than 30 years ago (Darnley et al., 1995).

According to the limited data that were found in literature, the typical Cu concentrations of soils that have developed on basement-rock deposits in Nigeria range between 8.7 and 24.5 mg kg^{-1} (Fagbami et al., 1985b). The typical Zn concentrations of soils in Nigeria range between 15 and 84 mg kg^{-1} (Udo & Fagbami, 1979). The only valid source of data on total Se concentrations was found in a book by Sillanpää and Jansson (1992), who described the mean total Se concentrations of soils in Nigeria to typically range between 0.02 and 33.2 mg kg^{-1}. Data on the water-soluble Se concentrations in Nigerian soils were not found (see Table 3.33).

Table 3.32 Total and water-soluble Se concentrations of soils in the Kaduna study area.

Detailed soil-type-specific data are given in Appendix B.

Study site	Dominant parent material	Horizon	Total		Water-soluble	
			Se		Se	
			Mean ± SD	Median	Mean ± SD	Median
			(mg kg^{-1})			
HR village	Pisolite slope deposits	A	0.5 ± 0.3	0.5	0.005 ± 0.002	0.006
		B	1.1 ± 0.6	1.2	0.005 ± 0.003	0.005
		C	1.2 ± 0.5	1.3	0.002 ± 0.001	0.002
	River deposits (clayey)	A	0.3 ± 0.1	0.3	0.004 ± 0.001	0.004
		B	0.4 ± 0.1	0.4	0.004 ± 0.000	0.004
		C	0.4	0.4	0.005	0.005
HR village mean			0.8 ± 0.5		0.004 ± 0.002	
LR village	Grus slope deposits	A	0.4 ± 0.4	0.2	0.006 ± 0.001	0.005
		B	0.9 ± 0.4	0.9	0.003 ± 0.002	0.003
	Pisolite slope deposits	A	0.1	0.1	0.005	0.005
		B	0.8 ± 0.4	0.8	0.005 ± 0.003	0.005
LR village mean			0.7 ± 0.5		0.004 ± 0.002	
Study-area mean			0.7 ± 0.7		0.004 ± 0.004	

[Total Se extracted with aqua regia; water-soluble Se extracted with deionized water; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

Compared to these Nigerian background levels, the soils in the Kaduna study area had normal total Cu and Zn concentrations. Generally, naturally high total micronutrient concentrations are known only in areas where soils developed on basalt slope deposits (see Table 3.33).

Table 3.33 Background total Cu and Zn concentrations of soils developed on different parent materials in Nigeria.

[Based on (1) Fagbami et al. (1985b); (2) Acquaye et al. (1972)]

Parent material	Total			Water-sol.	Ref.
	Cu	Zn	Se	Se	
	(mg kg^{-1})				
Grus slope deposits	16.7	28.8	na	na	(1)
River deposits (clayey)	8.7	12.1	na	na	(1)
Migmatite-gneiss complex slope deposits	24.5	32.3	na	na	(1)
Metasediment (schist) slope deposits	18.9	26.7	na	na	(1)
Sandstone (Continental Terminal) slope deposits	30.0	41.0	na	na	(2)
Basalt slope deposits	53.7	32.7	na	na	(1)

[Extracted with (1) a mixture of hydrogen fluoride, nitric acid and perchloric acid; (2) a mixture of nitric acid, sulfuric acid and perchloric acid; na: not available; Ref.: reference; water-sol.: water-soluble]

Critical limits for total Cu, Zn and Se and water-soluble Se concentrations in soils were those below 10 mg kg^{-1}, 20 mg kg^{-1}, 0.1 mg kg^{-1} and 0.003 mg kg^{-1}, respectively (Davies, 1996; Kabata-Pendias & Mukherjee, 2007; Tagwira et al., 1993; Tan, 1989) (see Table 3.33). Compared to these critical limits, the total Cu concentrations of the soils in the Kaduna study area were sufficient in the soils of the HR village Kaso (mean: 16.2 ±

4.9 mg kg^{-1}), but were low in the soils of the LR village Panzato (mean: 9.3 ± 4.7 mg kg^{-1}). This result is astonishing and leads one to believe that, although total Cu concentrations are low in Panzato, this may have no influence on the prevalence of CDR, as then the relationship should have been the other way around. However, as Cu was measured only as a total amount, the concentrations finally reaching crop plants remain unknown. Further analyses on plant-available concentrations of Cu are therefore needed to analyse its impact on plant nutrition in the Kaduna study area.

The total Zn concentrations were found to be normal in both the HR-village soils and the LR-village soils (HR village mean: 19.8 ± 5.1 mg kg^{-1}; LR village mean: 27.8 ± 14.5 mg kg^{-1}). But again, as only the total concentrations of Zn were measured, it was only possible to determine a primary deficiency, while whether there is also a secondary, plant-available Zn deficiency is unclear. This indicates that further analyses on the plant-available concentrations of Cu and Zn in the soils of the Kaduna study area are needed to check their possible impact on the soil-plant-human pathway.

In contrast, Se was analysed not only for the total concentrations (HR village mean: 0.8 ± 0.5 mg kg^{-1}; LR village mean: 0.7 ± 0.5 mg kg^{-1}) but also for their water-soluble concentrations (HR village mean: 0.004 ± 0.002 mg kg^{-1}; LR village mean: 0.004 ± 0.002 mg kg^{-1}). It thereby became apparent that total Se concentrations were sufficient, while the water-soluble Se concentrations were very near the range of deficiency in soils of the Kaduna study area. However, as water-soluble Se has a very narrow range between dietary deficiency and toxic concentration (Fordyce, 2013), one unit difference between the mean water-soluble Se concentrations in the soils of the Kaduna study area (0.004 ± 0.004 mg kg^{-1}) and the critical limit for this element (0.003 mg kg^{-1}) may already express sufficiency (see Tables 3.32 and 3.34).

Table 3.34 Critical Cu, Zn and Se soil limits linked to deficiency symptoms in food crops.

[Based on (1) Kabata-Pendias & Mukherjee (2007); Tagwira et al. (1993); (2) Davies (1996); (3) Tan (1989)]

Total			Water-sol.
Cu	**Zn**	**Se**	**Se**
(mg kg^{-1})			
< 10 (1)	< 20 (2)	< 0.1 (3)	< 0.003 (3)

[Extracted with (1) na; (2) na; (3) total Se: na; water-soluble Se: deionized water]

To become more certain about the magnitude of micronutrients in the soils of the Kaduna study area and their possible influence on human bone health, the micronutrient concentrations in soils of the Kaduna study area were again compared to those reported from other bone disease areas (see Table 3.35).

Cu deficiency in the soils of grazing areas in China were reported by Liu (2005) to have caused rickets in Bactrian camels. Liu (2005) states that the mean Cu content in the soils of this area is 10.5 mg kg^{-1}, while the mean Zn content is 23.0 mg kg^{-1} (see Table 3.35). Unfortunately, Liu (2005) does not mention the extractants that were used to measure the Cu and Zn concentrations in the grazing lands of the rachitic camels in China, wherefore comparisons to the study-area results were not possible. Pooley (1997) reported the Cu and Zn concentrations of the soils in the Mseleni-joint-disease area in South Africa to both be as low as 4.0 mg kg^{-1}, concentrations which are far below critical limits (see Table 3.34). However, the Cu and Zn concentrations in the soils of the Mseleni-joint-disease area were analysed after ammonium acetate ethylenediaminetetraacetic acid (EDTA) extraction, a laboratory method that was used only in a few studies and that failed to attract widespread use (Rayment & Lyons, 2011). Thus, comparisons to the study-area results were not possible.

With regard to background concentrations of total Se in soils of other bone disease areas, Fordyce (2013) reports that the total Se concentrations in soils of Kashin-Beck-disease areas typically range between 0.004 and 0.48 mg kg^{-1}. Li et al. (2009) state that Kashin-Beck disease occurs in areas where the total Se soil concentrations range between 0.1 and 0.2 mg kg^{-1}. According to Zhang et al. (2011), the critical limit of total Se are those of less than 0.1 mg kg^{-1} (see Table 3.35). The soils of the Kaduna study area can therefore be classified as containing, with an average of 0.7 ± 0.7 mg kg^{-1}, sufficient total Se concentrations (see Figure 3.9).

With regard to background concentrations of water-soluble Se in soils of other bone disease areas, Fordyce (2013) reports that the water-soluble Se concentrations concentrations of Kashin-Beck-disease areas typically range between 0.0003 and 0.005 mg kg^{-1} (see Table 3.35) and cites similar ranges from other Se-deficient areas in India and Sri Lanka. According to Tan (1989), water-soluble Se concentrations of less than 0.003 mg kg^{-1}, 0.003 to 0.006 mg kg^{-1} or 0.006 to 0.02 mg kg^{-1} are the critical limit for Se to be deficient, marginal or moderate to high, respectively. Compared to the results of this study, where the Kaduna study-area mean water-soluble Se concentration was 0.004 ± 0.004 mg kg^{-1} (see Table 3.32), the water-soluble Se concentrations in the soils of the Kaduna study area were classified to be marginal.

Table 3.35 Background total Cu, Zn and Se concentrations of soils in areas with rickets, Mseleni joint disease and Kashin-Beck disease.

[Based on (1) Liu (2005); (2) Pooley (1997); (3) Fordyce et al. (2000); (4) Tan (1989); (5) Zhang et al. (2011)]

Area	Total			Water-sol.	Ref.
	Cu	Zn	Se	Se	
	(mg kg^{-1})				
Rickets area in China	10.5 ± 6.8	23.0 ± 8.1	0.1	na	(1)
Mseleni-joint-disease area in South Africa	4.0	4.0	na	na	(2)
Kashin-Beck-disease area in Enshi District, China	na	na	0.1	< 0.005	(3)
Kashin-Beck-disease area in China	na	na	na	< 0.003	(4)
Kashin-Beck-disease area at the Tibetan Plateau, China	na	na	0.1	na	(5)

[Extracted with (1) na; (2) ammonium bicarbonate EDTA; (3) total Se: mixture of hydrogen fluoride, nitric acid and perchloric acid; water-soluble Se: deionized water; (4) deionized water; (5) mixture of hydrogen fluoride, nitric acid and perchloric acid; na: not available; Ref.: reference]

However, it should be noted at this point that it is not only low concentrations of Se per se which induce Se deficiency, but also processes of complexation and element interdependencies, which can affect Se availability. Fordyce et al. (2000) and Johnson et al. (2010) reported Se deficiency in areas with Kashin-Beck disease in China to be most severe in areas of high soil OC concentrations, where OC formed organo complexes with Se and thus amplified the Se deficiency in plants and humans. Whether such complexing mechanisms and element interdependencies further affect the marginal water-soluble Se concentrations of the soils in the Kaduna study area, is discussed in Chapter 3.4.10.

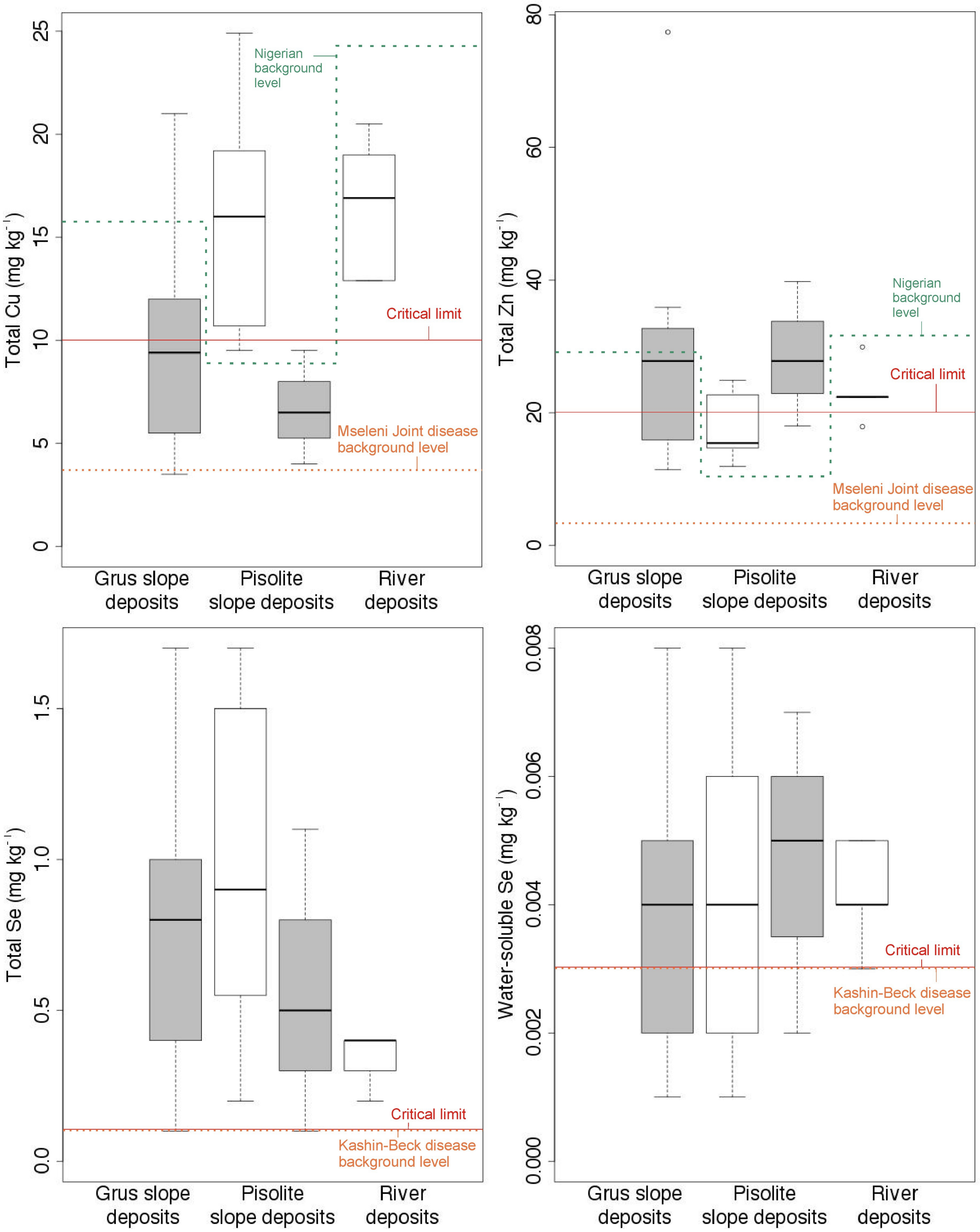

Figure 3.9 Total Cu, Zn, Se and water-soluble Se concentrations of soils developed on different parent materials in the Kaduna study area compared to background levels and critical limits.

[White bars represent the CDR-high-risk (HR) village Kaso; grey bars represent the CDR-low-risk (LR) village Panzato; dashed green lines represent Nigerian background levels (as given by Acquaye et al., 1972; Fagbami et al., 1985b); dotted orange lines represent background levels in areas with rickets, Mseleni joint disease and Kashin-Beck disease (as given by Fordyce et al., 2000; Pooley, 1997; Tan, 1989); solid red lines represent critical limits (as given by Davies, 1996; Kabata-Pendias & Mukherjee, 2007; Tagwira et al.,1993; Tan, 1989)]

In summary, the total micronutrient concentrations of the soils in the Kaduna study area were found in the order of Zn > Cu > Se. The water-soluble Se concentrations were two orders of magnitude lower than the total Se concentrations. Compared to Nigerian background levels, the total Cu concentrations were low in the soils of the Kaduna study area, while the total Zn and the total Se concentrations were within normal range. No data were found on the typical water-soluble Se concentrations in Nigerian soils. Compared to critical limits, the total Cu in the soils of the Kaduna study area was critically low only in the LR-village soils, while total Zn and total Se were present at normal concentrations. As Cu, however, was deficient only in the soils of the LR village, where the CDR prevalence rate is much lower than in the HR village, the low total Cu soil concentrations are not assumed to predispose to CDR, as otherwise the relationship should have been the other way around. The water-soluble Se was marginal in all the soils (see Figure 3.9). In conclusion, further analyses on the plant-available concentrations of micronutrients in the soils of the Kaduna study area are needed to determine not only the role of water-soluble Se in developing CDR, but also that of water-soluble Cu and water-soluble Zn.

3.4.9 Potentially toxic elements

There are a number of elements that are known to affect human health when elevated (Kabata-Pendias & Mukherjee, 2007). Among those, Al, Fe, Sr, Cd, Pb and F are especially hazardous to bones (Selinus et al., 2013). In such a way, an increase in Al intake via nutrition has been reported to lead to an accumulation of Al in bones (Krewski et al., 2009), to decrease Ca concentration in bones (Boudey et al., 1997), to promote histological changes in bones (Konishi et al., 1996) and to inhibit the mineralization of bones in young Ca-deficient rats (Rodriguez et al., 1990). An oversupply of Fe and Sr in the nutrition of laboratory animals has been found to cause low bone mass and to inhibit bone calcification (Baker & Halpin, 1991; Omdahl & DeLuca, 1971; Storey, 1961). Cd supplementation of laboratory rats leads to a decrease in bone strength (Ogoshi, 1989), while the Cd supplementation of mice induces bone deformities that especially become apparent in combination with a Ca-deficient diet (Wang et al., 1994). According to Kazantzis (2004), dietary Cd oversupply in adults causes osteoporosis. Moreover, elevated Pb concentrations in nutrition have been found to strongly affect the bone health of young chicken, especially under Ca-deficient conditions (Fullmer, 1991). In Nigeria, an environmental pollution with these elements is not uncommon (Nriagu, 1992; Nriagu et al., 1997).

Based on this knowledge, CDR has, by some medical scientists, been assumed to be caused by a dietary oversupply of Al, Fe, Sr, Cd, Pb and F (Cimma et al., 2004; Fischer et al., 1999; Keating et al., 2011; Özgür et al., 1996; Pfitzner et al., 2001). Since high concentrations of these elements in food crops depend on their concentrations in the soil (Agbenin, 1997; Adriano 1986; Millis et al. 2004), an oversupply of naturally or anthropogenically derived PTEs in the soils of the Kaduna study area were, in this study, thought to have possibly contributed to the local prevalence of CDR.

The analyses of soils in the study area showed the total Al concentrations were always higher than the total Fe concentrations, while their mean concentrations in the Kaduna study area's soils were 4.4 ± 2.0% and 2.7 ± 1.4%, respectively. The concentrations of total Al and Fe always increased with depth. In contrary, the total Sr concentrations tended to be highest in the topsoils, with a mean Sr concentration of 8.7 ± 6.6 mg kg^{-1} in the soils of the Kaduna study area (see Table 3.36).

The mean total Cd and Pb concentrations of the soils in the Kaduna study area were 0.005 ± 0.005 mg kg^{-1} and 16.8 ± 4.4 mg kg^{-1}, respectively. The Cd concentrations were highest in topsoils and the Pb concentrations were highest in subsoils (see Table 3.37).

Table 3.36 Total Al, Fe and Sr concentrations of soils in the Kaduna study area.
Detailed soil-type-specific data are given in Appendix B.

Study site	Dominant parent material	Horizon	Total Al		Total Fe		Total Sr	
			Mean ± SD	Median	Mean ± SD	Median	Mean ± SD	Median
			(%)				(mg kg^{-1})	
HR village	Grus slope deposits	A	nd	nd	1.8 ± 0.2	1.8	15.3 ± 8.1	20.0
		B	nd	nd	3.0 ± 0.6	2.8	17.3 ± 9.3	20.0
	Pisolite slope deposits	A	2.9 ± 0.4	3.0	2.0 ± 0.6	2.0	5.4 ± 2.7	5.0
		B	5.2 ± 1.8	5.2	2.4 ± 1.1	2.3	4.5 ± 3.7	3.5
		C	6.4 ± 1.2	6.5	4.4 ± 3.3	3.9	5.0 ± 0.0	5.0
	River deposits (clayey)	A	2.9 ± 0.2	2.9	3.3 ± 1.1	3.5	15.0 ± 13.4	9.9
		B	3.1 ± 0.2	3.1	2.5 ± 0.4	2.6	16.2 ± 7.5	15.0
		C	3.0	3.0	3.5	3.5	10.0	10.0
HR village mean			3.8 ± 1.9		2.8 ± 1.5		9.7 ± 7.9	
LR village	Grus slope deposits	A	3.7 ± 3.1	2.2	2.9 ± 2.1	2.2	10.1 ± 5.5	9.9
		B	4.9 ± 1.9	5.3	2.6 ± 1.1	2.7	7.1 ± 2.5	9.9
	Pisolite slope deposits	A	1.7	1.7	1.3	1.3	10.0	10.0
		B	4.0 ± 1.8	4.0	2.6 ± 0.7	2.6	7.5 ± 3.5	7.5
	River deposits	A	nd	nd	3.7	3.7	1.0	1.0
		B	nd	nd	2.6 ± 1.8	1.3	2.5 ± 0.7	2.5
		C	nd	nd	1.2	1.2	1.0	1.0
LR village mean			4.3 ± 2.2		2.6 ± 1.3		7.4 ± 4.2	
Study-area mean			4.4 ± 2.0		2.7 ± 1.4		8.7 ± 6.6	

[Total Al, Fe and Sr extracted with aqua regia; nd: not determined; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

The mean total F concentration in the soils of the Kaduna study area was 160.5 ± 79.7 mg kg^{-1}. The acid-soluble F concentrations were on average 8.0 ± 3.8 mg kg^{-1}, around 20-fold lower than the total F concentration. Both the total and the acid-soluble F concentrations increased with depth (see Table 3.38). According to Arnesen and Krogstad (1998), this is caused by an increase in the parent-material influence and higher contents of clay with lower soil depths.

Comparisons between the HR-village soils and the LR-village soils showed the mean total Fe, Sr, Cd and Pb concentrations to be higher in the soils of the HR village and the mean total Al, F and acid-soluble F concentrations to be higher in the soils of the LR village (see Figure 3.10 and Figure 3.11). The reason for the relatively increased Fe, Sr, Cd and Pb concentrations in the soils of the HR village was unknown, but elevated Cd concentrations, where mean concentrations were always highest in A horizons, were assumed to have possibly been caused by atmospheric influxes of a neighboured oil refinery (see Chapter 3.3).

Table 3.37 Total Cd and Pb concentrations of soils in the Kaduna study area.
Detailed soil-type-specific data are given in Appendix B.

Study site	Dominant parent material	Horizon	Total Cd		Total Pb	
			Mean ± SD	Median	Mean ± SD	Median
			(mg kg^{-1})			
HR village	Pisolite slope deposits	A	0.009 ± 0.004	0.009	14.1 ± 2.5	13.8
		B	0.003 ± 0.002	0.002	17.3 ± 1.1	17.3
		C	0.001 ± 0.001	0.001	20.5 ± 3.0	21.5
	River deposits (clayey)	A	0.007 ± 0.002	0.007	18.0 ± 5.0	18.0
		B	0.004 ± 0.004	0.005	20.4 ± 2.6	20.4
		C	0.002	0.002	20.8	20.8
HR village mean			0.005 ± 0.005		18.2 ± 3.4	
LR village	Grus slope deposits	A	0.007 ± 0.007	0.003	9.0 ± 0.3	9.0
		B	0.002 ± 0.002	0.003	17.0 ± 0.3	16.3
	Pisolite slope deposits	A	0.005	0.005	9.0	9.0
		B	0.003 ± 0.000	0.003	14.3 ± 2.7	14.3
LR village mean			0.004 ± 0.004		13.9 ± 4.8	
Study-area mean			0.005 ± 0.005		16.8 ± 4.4	

[Total Cd and Pb extracted with aqua regia; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

Table 3.38 Total and acid-soluble F concentrations of soils in the Kaduna study area.
Detailed soil-type-specific data are given in Appendix B.

Study site	Dominant parent material	Horizon	Total F		Acid-soluble F	
			Mean ± SD	Median	Mean ± SD	Median
			(mg kg^{-1})			
HR village	Grus slope deposits	A	130.0 ± 37.2	117.0	4.3 ± 1.6	3.5
		B	229.0 ± 92.8	238.0	10.4 ± 6.1	9.2
	Pisolite slope deposits	A	87.5 ± 11.3	85.5	6.1 ± 1.6	6.1
		B	106.3 ± 30.8	96.9	6.4 ± 1.2	7.0
		C	107.3 ± 23.0	102.7	10.7 ± 0.0	10.7
	River deposits	A	187.5 ± 139.3	187.5	5.4 ± 0.6	5.4
		B	229.0 ± 29.9	238.0	5.6 ± 0.4	5.8
HR village mean			140.0 ± 3.8		6.7 ± 0.2	
LR village	Grus slope deposits	A	127.6 ± 63.2	144.0	8.0 ± 0.0	8.0
		B	207.3 ± 101.2	228.0	11.8 ± 3.7	10.9
	Pisolite slope deposits	A	137.0	137.0	6.9	6.9
		B	213.5 ± 27.6	213.5	nd	nd
LR village mean			188.5 ± 85.3		10.7 ± 3.5	
Study-area mean			160.5 ± 79.7		8.0 ± 3.8	

[Total F extracted in a mixture of sodium hydroxide, deionized water and hydrogen chloride; acid-soluble F extracted in a mixture of hydrochloric acid, sodium citrate, sodium acetate and deionized water; nd: not determined; HR village (Kaso): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%]

The Fe and Pb concentrations of the soils in the HR village increased with depth, which were assumed to have been caused by the geochemical influences of the different parent materials (see Chapter 3.2). In contrast, Sr was always the highest in B horizons, where it is typically sorbed by clay minerals (Kabata-Pendias & Mukherjee, 2007; Tijani et al., 2006). The higher concentrations of F and Al in the soils of the LR village were assumed to be caused by the dominance of biotite-containing grus slope deposits in the LR village (see Chapter 3.2).

Table 3.39 Background total Al, Fe, Sr, Cd, Pb and F as well as background acid-soluble F concentrations of uncontaminated soils worldwide.

[Based on (1) Kabata-Pendias & Mukherjee (2007); (2) Adriano (1986); Alloway (1995); Waldron (1980); (3) Cronin et al. (2000); Jha et al. (2008); Loganathan et al. (2001); Ozsvath (2009); (4) Arnesen (1997); Fiedler & Rösler (1993); Xie et al. (2001)]

Total						Acid-sol.
Al	**Fe**	**Sr**	**Cd**	**Pb**	**F**	**F**
(%)		**(mg kg^{-1})**				
1-4 (1)	0.1-10 (1)	32-150 (1)	0.06-1 (2)	0.8-80 (1)	< 200 (3)	< 20 (4)

[Extracted with (1) na; (2) NaOH; (3) HCl]

No literature was found describing PTE concentrations of uncontaminated sites in Nigeria, so the soil results of this study were compared to worldwide background levels. According to Kabata-Pendias and Mukherjee (2007), the background levels of total Al, Fe, Sr and Pb are typically between 1% to 4%, 0.1% to 10%, 32 mg kg^{-1} to 150 mg kg^{-1} and 0.8 mg kg^{-1} to 80 mg kg^{-1}, respectively. For the total Cd concentrations, Adriano (1986), Alloway (1995) and Waldron (1980) reported world background levels ranging between 0.06 mg kg^{-1} and 1 mg kg^{-1}. According to Cronin et al. (2000), Jha et al. (2008) and Loganathan et al. (2001), total (NaOH extracted) F concentrations of less than 200 mg kg^{-1} are suitable for serving as an F background level for uncontaminated soils. For acid-soluble F, Arnesen (1997), Fiedler and Rösler (1993) and Xie et al. (2001) state that acid-soluble F soil concentrations below 20 mg kg^{-1} are typical for uncontaminated sites (see Table 3.39).

Compared to these world background levels, the soils of the Kaduna study area had slightly increased concentrations of total Al, were low in total F, were low to very low in acid-soluble F and were very low in Fe, Sr, Cd and Pb (compare Tables 3.36 and 3.39). Similar findings from the same study area but from different study sites during former Master (*Diplom*) studies are described in Hartmann (submitted).

The only element which was identified as being slightly elevated was total Al. The reason for the relatively increased Al concentrations of the soils in the Kaduna study area was, in all probability, the mineral composition of the granitoid bedrock and the grus parent material, containing Al-bearing minerals, such as biotite, feldspars and plagioclase (see Chapter 3.1).

Table 3.40 Critical Al, Fe, Sr, Cd, Pb and F soil limits linked to toxicity symptoms in food crops.

[Based on (1) Jones & Bennett (1986); (2) Kabata-Pendias & Mukherjee (2007); (3) Ozsvath (2009); (4) Arnesen (1997); Eyde (1983)]

Total						Acid-sol.
Al	**Fe**	**Sr**	**Cd**	**Pb**	**F**	**F**
(%)		**(mg kg^{-1})**				
> 7 (1)	> 10 (2)	> 250 (2)	> 1 (2)	> 80 (2)	> 1000 (3)	> 150 (4)

[Extracted with (1) na; (2) na; (3) na; (4) HCl]

According to Jones *and* Bennett (1986), Kabata-Pendias and Mukherjee (2007), Ozsvath (2009), Arnesen (1997) and Eyde (1983), the critical limits of total Fe, total Sr, total Cd, total Pb, total F and acid-soluble F are 10%, 250 mg kg^{-1}, 1 mg kg^{-1}, Pb 80 mg kg^{-1}, 1000 mg kg^{-1} and 150 mg kg^{-1}. Compared to these critical limits, the mean total concentrations of Fe, Sr, Cd, Pb, F as well as the mean acid-soluble concentrations of F in the soils of the Kaduna study area were with 2.7%, 8.7 mg kg^{-1}, 0.005 mg kg^{-1}, 16.8 mg kg^{-1}, 160.5 mg kg^{-1} and 8.0 mg kg^{-1} found to be within normal ranges (compare Tables 3.36, 3.38 and 3.40 and see Figure 3.10 and Figure 3.11).

Only the total Al concentrations in the study area's soils were with 4.4 ± 2.0% on average relatively close to the critical limit of 7% (see Table 3.40 and Figure 3.10). High Al concentrations can damage plants directly and causes shallow rooting, drought susceptibility and nutrient deficiencies in plants (Foy, 1984). Al is easily taken up by plants, especially in acid environments (Delhaize & Ryan, 1995; Kamprath, 1970) and can then enter human bodies, as food is the most important source of Al in human (Rengel, 2004). However, according to Jones and Bennett (1986) and Scheffer and Schachtschabel (2002), only the soluble and exchangeable Al in soils is potentially toxic to plants and humans and not the total Al. Lindsay (1979) further stated that total Al concentrations in soils can even be as high as 30% without posing any risk to plants or human health. According to Smith et al. (1996), who found dissolved Al concentrations in water from an aquifer hosted within the West African crystalline basement to be generally low, the water-soluble Al concentrations in the ecosystems of the Kaduna study area should be low too. Further analyses on the soluble and exchangeable Al concentrations on the soils of the Kaduna study area were considered to be necessary to finally assess the toxicity potential of Al in this area.

Table 3.41 Background total Sr, Cd, Pb and F as well as acid-soluble F concentrations of soils in areas with rickets, CDR, Itai-Itai disease and fluorosis.
[Based on (1) Özgür et al. (1996); (2) Pfitzner et al. (2001); (3) Cai et al. (1990); (4) Fung et al. (1999); (5) Walton (1988); (6) Shomar et al. (2004)]

Area	Total				Acid-soluble	Ref.
	Sr	Cd	Pb	F	F	
	(mg kg^{-1})				(mg kg^{-1})	
Rickets are in Turkey	> 350	na	na	na	na	(1)
CDR area in Jos City, northern Nigeria	na	na	> 71	na	na	(2)
Itai-Itai disease area in Japan	na	> 1.0	na	na	na	(3)
Dental fluorosis area in China	na	na	na	> 383	na	(4)
Skeletal fluorosis area in New Zealand	na	na	na	1425	na	(5)
Dental fluorosis in Gaza strip	na	na	na	na	> 178	(6)

[Extracted with (1) data as given by maps; (2) na; (3) HNO_3 and H_2O_2; (4) NaOH; (5) na; (6) citric acid; Ref.: reference; na: not available]

Comparing the PTE concentrations of the soils in the Kaduna study area to Sr, Cd, Pb and F background concentrations in the soils of other endemic bone disease areas showed the PTE concentrations in the soils of the study area to be very low (compare Tables 3.40 and 3.41). Özgür et al. (1996) reported the total Sr soil concentrations in rickets areas in Turkey to be greater than 350 mg kg^{-1}. Cai et al. (1990) described total Cd soil concentrations of less than 1.0 mg kg^{-1} in areas of Itai-Itai bone disease in Japan. In Jos City, where CDR is prevalent in around 9% of the population, Pb concentrations of at least 71 mg kg^{-1} were found in the local soils (Pfitzner et al., 2001; 1998). In China, total F soil concentrations of less than 383 mg kg^{-1} are known in areas of dental fluorosis (Fung et al., 1999). Shomar et al. (2004) found acid-soluble F soil concentrations to be at a minimum of 178 mg kg^{-1} in areas of dental fluorosis in the Gaza strip. Total F concentrations of 1425 mg kg^{-1}were reported from areas with skeletal fluorosis in New Zealand (Walton, 1988).

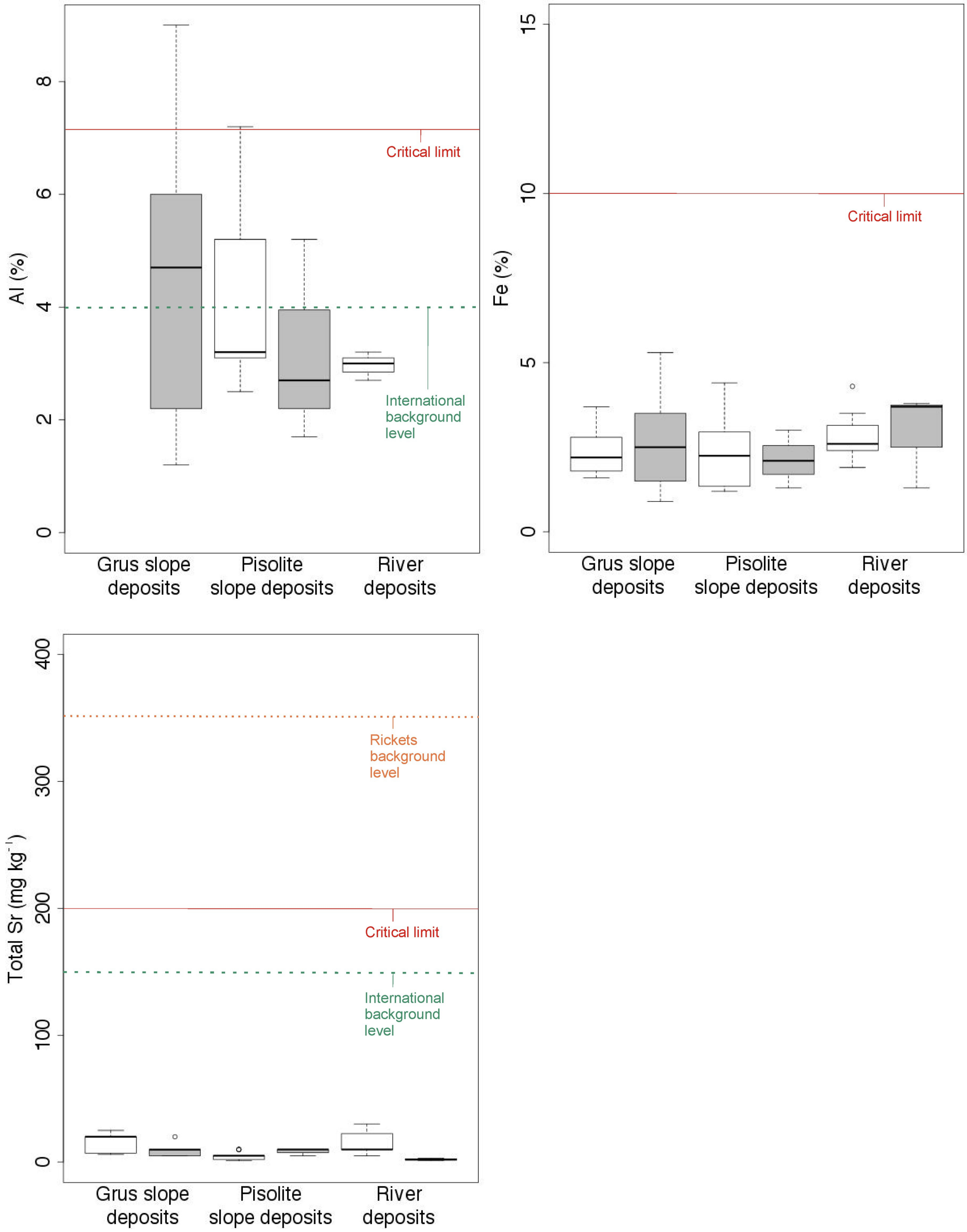

Figure 3.10 Total Al, Fe and Sr concentrations of soils developed on different parent materials in the Kaduna study area compared to background levels and critical limits.

[White bars represent CDR-high-risk (HR) village Kaso: CDR prevalence rate > 5%; grey bars represent CDR-low-risk (LR) village Panzato: CDR prevalence rate ≤ 5%; dotted orange line represents background level in a rickets area (as given by Özgür et al., 1996); solid red lines represent critical limits (as given by Kabata-Pendias & Mukherjee, 2007)]

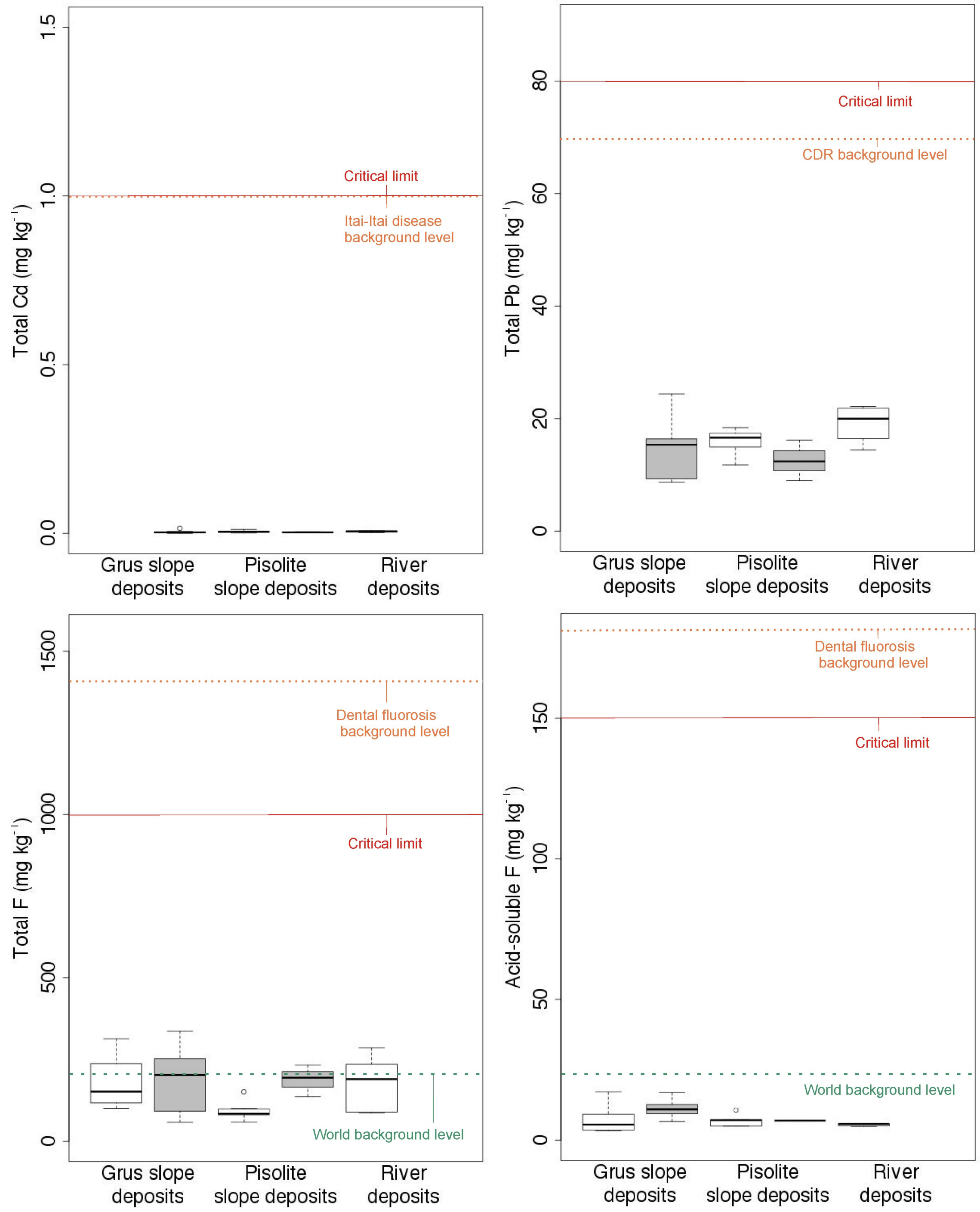

Figure 3.11 Total Cd, Pb, F and water-soluble F concentrations of soils developed on different parent materials in the Kaduna study area compared to background levels and critical limits.

[White bars represent the CDR-high-risk (HR) village Kaso; grey bars represent the CDR-low-risk (LR) village Panzato; dashed green lines represent world background levels (as given by Arnesen, 1997; Cronin et al., 2000; Fiedler & Rösler, 1993; Jha et al., 2008; Kabata-Pendias & Mukherjee, 2007; Loganathan et al., 2001; Ozsvath, 2009; Xie et al., 2001); dotted orange lines represent soil background levels in areas with Itai-Itai disease, CDR and fluorosis (as given by Cai et al., 1990; Fung et al., 1999; Pfitzner et al., 2001; Shomar et al., 2004); solid red lines represent critical limits (as given by Arnesen, 1997; Eyde, 1983; Kabata-Pendias & Mukherjee, 2007; Ozsvath, 2009)]

The mean total concentrations of Al, Fe, Sr, Cd, Pb and F as well as the mean acid-soluble concentrations of F in the soils of the Kaduna study area, which were around 4.4%, 2.7%, 8.7 mg kg^{-1}, 0.005 mg kg^{-1}, 16.8 mg kg^{-1}, 160.5 mg kg^{-1} and 8.0 mg kg^{-1}, respectively, were significantly lower than these background values (compare Table 3.37, Table 3.38 and Table 3.41 and see Figure 3.10 and Figure 3.11).

Although this comparison may indicate that the PTE concentrations in the soils of the Kaduna study area do not, in all probability, predispose to the CDR in this area, it has to be mentioned that measuring total element concentrations in soils is not suitable to estimate their bioavailability and thus their influence on plant health and human bone health (Alloway, 2013; Hough, 2010; Laing, 2010; Scheffer & Schachtschabel, 2002). In conclusion, further analyses are needed measuring the plant-available concentrations of PTEs in the soils of the Kaduna study area.

In summary, the soils in the Kaduna study area were slightly increased with respect to total Al, low in total F and very low in total Fe, total Sr, total Cd, total Pb and acid-soluble F compared to world background levels. In the soils of the HR village Kaso, the total Fe, total Sr, total Cd and total Pb concentrations were higher than those in the soils of the LR village Panzato, where the total Al and total F concentrations were increased. These differences were assumed to be caused by differences in the parent materials and land-use conditions between the study sites. Compared to the critical limits, none of the PTEs was elevated in the soils of the Kaduna study area. Compared to the background levels that were reported from other bone disease areas, the soils of the Kaduna study area contained very low total concentrations of PTEs (see Figure 3.10 and Figure 3.11). Further analyses on the plant-available concentrations of the PTEs are needed to finally assess the impact of the soil pollution on the cause of the CDR in the Kaduna study area.

3.4.10 Element availability and interdependencies

The availability of macronutrients, micronutrients as well as PTEs from soils to plants is not only a function of their total, plant-, acid- or water-soluble concentrations in soils but is also controlled by element interdependencies in soils (Arshad & Martin, 2002). Amongst others, the pH values and the OC contents are known to influence the availability of elements in soils (Brady & Weil, 1999; Davies & Mundalamo, 2010). For example, it is known from endemic Kashin-Beck-disease areas in China that high concentrations of OC in the local soils have caused the water-soluble Se concentrations to be heavily complexed and therefore to be unavailable to plants (Fordyce et al., 2000; Wang & Gao, 2001). To check if element interdependencies are of environmental concern also in the soils of the Kaduna study area, Spearman's rank correlation coefficients (rhos), which show the statistical dependence of two variables, were calculated for some selected soil parameters (see Table 3.42).

According to Table 3.42, a positive correlation was found between sand and pH, meaning that the higher the amounts of sand, the higher the pH values. This correlation is, in all probability, caused by the fact that the sand in the Kaduna study area is a weathering product of the cation-rich Older Granites and grus, causing the pH values to be elevated in soils underlain by grus (see Chapter 3.4.5). Furthermore, a positive correlation was also found between sand and total F, which is, in all probability, caused by the high contents of F-bearing biotite minerals in the grus fractions, meaning that the higher the amounts of sand in a soil, the higher the total F concentrations. The highest grus contents were found in the LR-village soils, which also had the highest pH values and F concentrations (see Chapters 3.2.1.1, 3.4.5 and 3.4.9).

Table 3.42 Spearman's rank correlation coefficients for selected physicochemical parameters of soils in the Kaduna study area.

							Plant-avail.				Total			Water-sol.	Total					
		sand	**silt**	**clay**	**pH**	**OC**	**Ca**	**Mg**	**K**	**P**	**Cu**	**Se**	**Zn**	**Se**	**Al**	**Fe**	**Sr**	**Cd**	**Pb**	**F**
	silt	**-0.84**																		
	clay	-0.55	0.09																	
	pH	**0.80**	**-0.71**	-0.41																
	OC	0.28	-0.12	-0.22	0.05															
Plant-avail.	**Ca**	0.52	-0.42	-0.16	**0.85**	0.17														
	Mg	0.36	-0.27	-0.16	**0.80**	-0.01	**0.86**													
	K	0.50	**-0.64**	-0.03	**0.81**	-0.26	**0.70**	**0.62**												
	P	0.45	-0.22	**-0.68**	0.44	0.49	0.26	0.28	0.09											
Total	**Cu**	**-0.68**	0.51	**0.61**	**-0.82**	-0.38	**-0.66**	**-0.67**	-0.48	**-0.84**										
	Se	-0.20	0.03	**0.67**	-0.32	-0.31	-0.09	-0.25	-0.12	**-0.81**	**0.70**									
	Zn	-0.21	-0.08	0.33	-0.01	**-0.60**	-0.16	0.01	0.43	-0.50	0.33	0.09								
Water-sol.	**Se**	0.54	-0.55	-0.15	0.29	0.32	0.07	-0.09	0.21	0.39	-0.26	-0.06	-0.01							
Total	**Al**	-0.46	0.30	**0.62**	-0.44	-0.54	-0.24	-0.20	-0.26	**-0.87**	**0.78**	**0.87**	0.29	-0.28						
	Fe	0.20	-0.27	0.29	0.06	-0.07	0.01	0.03	0.22	-0.48	0.32	0.47	0.37	0.23	0.29					
	Sr	0.15	0.13	**-0.76**	0.27	-0.04	0.00	0.25	0.08	**0.72**	**-0.57**	**-0.87**	-0.03	0.02	**-0.65**	-0.42				
	Cd	0.24	-0.12	-0.15	0.05	**0.89**	0.20	0.03	-0.31	0.31	-0.34	-0.21	**-0.56**	0.11	-0.32	-0.24	-0.17			
	Pb	**-0.92**	**0.69**	**0.58**	**-0.75**	-0.44	**-0.56**	-0.36	-0.39	**-0.64**	**0.74**	0.27	0.39	**-0.69**	0.54	-0.05	-0.22	-0.32		
	F	**0.62**	**-0.72**	-0.07	0.46	-0.29	0.09	0.19	0.43	-0.17	-0.15	0.15	0.33	0.17	0.07	**0.56**	-0.08	-0.23	-0.31	
Acid-sol.	**F**	0.09	-0.04	-0.04	**0.58**	-0.45	**0.66**	**0.80**	**0.62**	-0.11	-0.26	-0.01	0.41	-0.16	0.20	0.06	0.17	-0.33	-0.07	0.12

[positive rhos show positive correlation; negative rhos show negative correlation; rhos highlighted in bold are statistically significant ($p < 0.05$)]

A positive correlation was found between the silt and the Pb, as well as the clay and the Pb (see Table 3.42), which is due to the general affinity of Pb to the fine granulometric fractions of a soil (Kabata-Pendias & Mukherjee, 2010). Apart from total Pb, also the total Cu, the total Se and the total Al were positively correlated to the clay (see Table 3.42), meaning that the higher the clay contents, the more complexed the total Ca, Se, Al and Pb.

Apart from that, a statistically significant positive correlation was identified between the pH and the plant-available Ca, the pH and the plant-available Mg, the pH and the plant-available K as well as the pH and the acid-soluble F, showing that the availability of Ca, Mg and K and F is highest in the soils with the highest pH values (see Table 3.42). As the highest pH values were found in the LR-village soils that had developed on grus slope deposits (see Chapters 3.2.1.1), the availability of the macronutrients as well as F was assumed to be highest in the soils of the LR village Panzato.

A statistically significant negative correlation was found between the pH and the total Cu as well as the pH and the total Pb (see Table 3.42), showing that Cu and Pb are most available under low pH values. As the lowest pH levels were found in the HR-village soils, the total Cu and Pb concentrations were assumed to be most available in the soils of the HR-village study site. However, as the Cu concentrations were not deficient and the Pb concentrations not hazardously elevated in the soils of the HR study site, the higher availability of these elements was considered unlikely to have a further detrimental effect on the soil-plant-human pathway in this area.

Apart from the pH values, also the OC contents are known to typically control the availability of certain soil elements. In the Kaduna study area, a statistically significant positive correlation was found between the OC and the total Cd (see Table 3.42), indicating that Cd is complexed by OC. However, as the total Cd concentrations of the soils in the Kaduna study area were very low, a binding between OC and Cd may only strengthen the already low Cd concentrations (see Chapter 3.4.9) but should not have a detrimental effect on the soil-plant pathway.

The statistically significant positive correlation between the plant-available Ca and the plant-available Mg, the plant-available Ca and the plant-available K as well as the plant-available Ca and the acid-soluble F (see Table 3.42) is a normal phenomenon between these elements and is also found in other soils in the northern guinea savanna (Landon, 1991). As the Ca is the most abundant macronutrient in the soils of the Kaduna study area (see Chapter 3.4.7), the availability of Mg, K and F may be slightly reduced in the soils of the Kaduna study area.

A statistically significant positive correlation was also found between the plant-available P and the total Sr (see Table 3.42). As a correlation between P and Sr is known to be most often caused by high applications of P fertilizers and manure (Kabata-Pendias & Mukherjee, 2010), the use of P fertilizers and manure in the Kaduna study area was assumed to may have brought about an increased input of Sr in the soils of the Kaduna study area. However, as the amounts of fertilizers used in the Kaduna study area (see Chapter 3.3) as well as the Sr concentrations measured in the soils of the study area were both low (see Chapter 3.4.9), a Sr contamination or a P deficiency due to the binding between these elements, was considered to be unlikely.

The statistically significant negative correlation between the plant-available P and the total Cu as well as the plant-available P and the total Se further indicates that increased P fertilization may reduce the availability of Se and Cu in the soils of the Kaduna study area.

However, as the natural concentrations of P in the soils as well as the use of P fertilizers are low in the rural CDR study sites (see Chapters 3.3 and 3.4.8), a complexation between P and Cu as well as P and Se is unlikely for the Kaduna study area.

A statistically significant positive correlation was also found between the total Cu and the silt, the total Cu and the total Se, the total Cu and the total Al as well as the total Cu and the total Pb (see Table 3.42), indicating that the complexation of Cu is high in soils containing high contents of silt and high concentrations of Se, Al and Pb, which are typical for the soils in the HR village Kaso (see Chapters 3.4.8 and 3.4.9). In contrast, the availability of Cu is high in soils containing high contents of sand, high pH levels and high concentrations of Ca, Mg and P. Such physicochemical conditions were typical for the soils that had developed in the LR village Panzato. A Cu-deficiency in the soils of the HR village was therefore considered likely. However, as no measurements were made on the plant-available Cu concentrations in the soils of the Kaduna study area, no verification of this result was possible. Further analyses on the plant-available Cu concentrations are recommended.

The water-soluble Se concentrations were negatively correlated with the total Pb concentrations (see Table 3.42), indicating that the availability of Se is lowest in soils with increased Pb concentrations. As Pb was highest in the soils of the HR village Kaso (see Chapter 3.4.9), the Se availability was assumed to be lowest in the soils of this study site. However, the Pb concentrations, which were assumed to be elevated in the pisolite-slope-deposit dominated HR-village soils, were very low compared to the critical limits. Although the correlation between the water-soluble Se and the total Pb was statistically significant, the rho was with -0.56 still relatively low (see Table 3.42). The low rho indicates that the complexation between water-soluble Se and total Pb is not strong enough to result in Se deficiency. Furthermore, according to Tan (2002), soils which have developed on ferricretes or pisolite slope deposits still have relatively high total and water-soluble Se concentrations, a fact that was also confirmed by the statistically positive correlation between the total Se and the total Al in the soils of the Kaduna study area (see Table 3.42). A Se deficiency due to the complexation between Pb and Se was therefore considered unlikely for the soils of the Kaduna study area.

In summary, although interdependencies were found between certain elements in the soils of the Kaduna study area, most of these bindings were not strong enough to lead to a critical complexation of macronutrients and micronutrients or to a critical increase in the availability of certain PTEs.

3.5 Drinking water

Apart from analysing bedrock, land use, parent materials and soils, geomedical analyses commonly include the analysis of water geochemistry, as the availability of elements ingested in water is close to 100% (Hough, 2010). Especially in developing countries, the chemistry of water is of great importance, as both ground and surface water is often directly used as drinking water (Dissanayake & Chandrajith, 2009). In the Kaduna study area, the drinking water samples were measured for pH, Ca, F and Se, as these three elements are most likely to have the greatest potential influence on human bone health.

Analyses on the pH values as well as Ca, F and Se concentrations of the drinking water in the Kaduna study areas showed mean pH values, Ca, Se and F concentrations of 5.5 ± 1.4, 4.4 ± 3.9 mg L^{-1}, 0.5 ± 1.0 µg L^{-1} and 0.2 ± 0.2 mg L^{-1}, respectively. Comparisons between the study sites showed the mean pH values to be lowest in the LR-village water, the mean Ca concentrations to be lowest in the HR-village water, the mean Se concentrations to be lowest in both the LR-village and the NR-village water and the mean F concentrations to be higher in the LR-village drinking water than in the HR-village drinking water (see Tables 3.43 and 3.44).

Table 3.43 pH values as well as Ca and Se concentrations of drinking water in the Kaduna study area.

Detailed area and source-specific data are given in Appendix C.

Study site	Source	n	pH		Ca		Se	
			Mean ± SD	Median	Mean ± SD	Median	Mean ± SD	Median
					(mg L^{-1})		(µg L^{-1})	
HR villages	SW	10	5.3 ± 0.9	5.0	2.0 ± 1.7	1.0	nd	nd
	GW	5	5.4 ± 1.6	4.5	3.9 ± 4.5	2.0	0.6 ± 1.1	0.1
HR villages mean			5.4 ± 1.4		3.5 ± 3.6		0.7 ± 1.1	
LR village	SW	1	5.0	5.0	11.0	11.0	nd	nd
	GW	1	5.0	5.0	6.0	6.0	0.1	0.1
LR village mean			5.0 ± 0.0		8.5 ± 3.5		0.1 ± 0.0	
NR village	SW	1	7.5	7.5	nd	nd	nd	nd
	GW	1	6.0	6.0	8.0	8.0	0.1	0.0
NR village mean			6.8 ± 1.1		8.0 ± 0.0		0.1 ± 0.0	
Study-area mean		19	5.5 ± 1.4		4.4 ± 3.9	3.5	0.5 ± 1.0	0.1

[SW: surface water; GW: groundwater; nd: not determined; HR villages (Pam Madaki, Ungwan Bagudu, Koche Koche, Kaso, Telele, Ungwan Fada, Jankassa): CDR prevalence rate > 5%; LR village (Kafari): CDR prevalence rate ≤ 5%; NR village (Dakala): CDR prevalence rate = 0%]

The typical background pH value of drinking water in Older-Granite areas in northern Nigeria is around 6.4 near Katsina City (Preez & Barber, 1965) and in soils near Zaria City, the typical pH background values is between 6.9 and 7.2 (Anudu et al., 2011). These pH values are significantly lower than those found in soils of areas underlain by schist- or basalt-derived parent materials (see Table 3.45). Compared to the pH background levels known from other Older-Granite areas, the mean pH value of the drinking water in the Kaduna study area, which was 5.5 ± 1.4, was low (see Table 3.43).

The typical Ca background levels of drinking water in basement-rock areas in northern Nigeria are around 18.0 mg L^{-1} near Katsina City (Preez & Barber, 1965) and between 9.4 and 36.1 mg L^{-1} near Zaria City (Anudu et al., 2011). Compared to these background levels, the Ca concentration of the drinking water in the Kaduna study area, which was 4.4 ± 3.9 mg L^{-1} on average, is clearly lower. However, the relatively higher Ca concentrations of the drinking water in Katsina City and Zaria City are assumed to be due to the geochemical influences of schist, a bedrock type which is known to provide Ca concentrations in water of even up to 40 mg L^{-1}. Similarly high Ca concentrations are known from basaltic-influenced areas in northern Nigeria (see Table 3.45). According to a study of Turaki (2007), who conducted drinking water analyses in the CDR villages Gonin Gora, Jankassa and Kaso (see Figure 3.7), the average Ca concentration of the drinking water in the Kaduna study area is 4.6 mg L^{-1}, which is fully in agreement with the results of this study. The Ca concentrations of the drinking water in the study area are found to be relatively low compared to the Ca concentration of drinking water in northern Nigerian basement-rock areas, but are normal compared to the Ca background levels in Older-Granite areas in northern Nigeria.

Table 3.44 F concentrations of drinking water in the Kaduna study area.
Detailed area and source-specific data are given in Appendix C.

Study site	Source	n	F Mean ± SD (mg L⁻¹)	F Median (mg L⁻¹)
HR villages	SW	10	0.1 ± 0.0	0.1
	GW	5	0.1 ± 0.0	0.1
HR villages mean			0.1 ± 0.0	
LR villages	SW	1	nd	nd
	GW	1	0.4	0.4
LR villages mean			0.4 ± 0.1	
NR village	SW	1	nd	nd
	GW	1	nd	nd
NR villages mean			nd	
Study-area mean		19	0.2 ± 0.2	0.1

[SW: surface water; GW: groundwater; nd: not determined; HR villages (Pam Madaki, Ungwan Bagudu, Koche Koche, Kaso, Telele, Ungwan Fada, Jankassa): CDR prevalence rate > 5%; LR village (Kafari): CDR prevalence rate ≤ 5%; NR village (Dakala): CDR prevalence rate = 0%]

Finding background levels for the Se concentrations of the drinking water in northern Nigeria was difficult (see Table 3.45), since Se measurements have been neglected in environmental studies for many years (Darnley et al., 1995). According to Jatau et al. (2008), the Se concentrations of the drinking water near Kaduna City, northern Nigeria, typically range between 0.04 and 0.14 µg L^{-1}. Asubiojo et al. (1997) reported Se concentrations of tap and groundwater in southern Nigeria to typically be 0.17 µg L^{-1} and 2.33 µg L^{-1}, respectively. Compared to these background levels, the Se concentrations of the drinking water in the Kaduna study area seemed, with 0.5 ± 1.0 µg L^{-1} on average, to be elevated at first sight. However, as already indicated by the high SD, the Se concentrations measured in the water of the Kaduna study area contained an outlier (see Figure 3.12), which biased the mean Se concentration. Taking the Se study-area median of 0.1 µg L^{-1} was identified as being a statistically more robust comparison and showed that the Se concentrations of the water in the Kaduna study area were finally in total agreement with the northern Nigerian background level.

Table 3.45 Background pH values as well as Ca and F concentrations of groundwater in different bedrock areas of northern Nigeria.
[Based on (1) Preez & Barber (1965); (2) Anudu et al. (2011)]

Dominant bedrock	pH	Ca (mg L⁻¹)	F (mg L⁻¹)	Ref.
Older Granites (around Katsina City)	6.4	18.0	0.1	(1)
Migmatite-gneiss complex (near Zaria City)	6.8	16.7	na	(2)
Metasediments (near Zaria City)	7.0	36.1	na	(2)
Sandstone (around Gombe City)	6.6	28.1	0.0	(1)
Basalt (at the Jos Plateau)	7.3	41.0	0.0	(1)

(na: not available; Ref.: reference)

The worldwide background level of F in natural waters typically ranges between 0.05 and 2.7 mg L^{-1} (Kabata-Pendias & Mukherjee, 2007), while F concentrations are known to be particularly high in areas of acidic igneous bedrocks, which contain high concentrations of F-bearing minerals, such as biotite or apatite (Reimann & Caritat, 1998). Furthermore, F is typically high in marine-sediment and limestone dominated areas (Edmunds & Smedley, 2013).

In northern Nigeria, Preez and Barber (1965) reported Older-Granite background levels to be around 0.1 mg L^{-1} on average (see Table 3.45). Analyses on F in the surface water around Zaria City, northern Nigeria, showed mean F concentrations to typically range between 0.1 and 0.2 mg L^{-1} (Paul et al., 2011). Compared to this range, the F concentrations of the drinking water in the Kaduna study area were, with a mean F content of 0.2 ± 0.2 mg L^{-1} (see Table 3.44), normal to slightly elevated. Compared to the world F background level, the F concentrations of the drinking water in the Kaduna study area was low.

According to the WHO (2011; 2009), the regular consumption of drinking water containing Ca concentrations of less than 1 mg L^{-1}, Se concentrations below 0.01 µg L^{-1} or F concentrations greater than 1.5 mg L^{-1} lead to the development of Ca- and Se-deficiency or F-toxicity symptoms in humans (see Table 3.46). Compared to these critical limits, the average Ca, Se and F concentrations of the drinking water in the Kaduna study area, with 4.4 ± 3.9 mg L^{-1}, 0.1 µg L^{-1} and 0.2 ± 0.2 mg L^{-1}, respectively, were significantly higher or lower. This indicates that the Ca and Se concentrations of the drinking water in the Kaduna study area are too high and the F concentrations in the drinking water are too low to have caused Ca deficiency, Se deficiency or F toxicity in humans.

The typical Se concentrations in drinking water of areas with Kashin-Beck disease range between 0.005 and 0.44 µg L^{-1} (Fordyce, 2013) and are on average always lower than 0.08 µg L^{-1} (Zhang et al., 2011). Compared to these Kashin-Beck-disease background levels, the median Se concentration of the drinking water in the Kaduna study area was with 0.1 µg L^{-1} comparably low (see Tables 3.43 and 3.47).

Table 3.46 Critical Ca, Se and F limits of drinking water linked to deficiency or toxicity symptoms in humans.

[Based on WHO (2011; 2009)]

Ca (mg L^{-1})	Se (µg L^{-1})	F (mg L^{-1})
< 1	< 0.01	> 1.5

In areas around Lake Naivasha in Kenya, where dental fluorosis is endemic, the typical F concentrations in drinking water range between 1.7 and 1.8 mg L^{-1} (Jones et al., 1977). In some areas of Ghana, where the local population suffer dental fluorosis, the F concentrations are typically greater than 3.0 mg L^{-1} due to high contents of F-bearing minerals in the granitoid basement rocks (Smedley et al., 1995). According to Dissanyake and Chandrajith (2009), F concentrations of greater than 4 mg L^{-1} cause skeletal deformities and fluorosis in children of Sri Lanka. In granitoid areas of Rajasthan, India, the F concentrations of drinking water are as high as 18.0 mg L^{-1}, having detrimental effects on the health of the population (Maithani et al., 1998). In some fluorosis areas of Tanzania, the mean F concentrations of drinking water are even as high as 1281 mg L^{-1} (Edmunds & Smedley, 2013). Compared to these background levels, the median F content of the drinking water in the Kaduna study area of 0.1 mg L^{-1} was too low to have any effect on bone health in this area (see Tables 3.44 and 3.47). A finding that has also been described by Pettifor et al. (2008) (see Chapter 3.7.4).

However, according to Edmunds and Smedley (2013; 1996) and Welch et al. (1998), the natural problems of groundwater toxicities may have been exacerbated over the last three decades by widespread deep drilling and the installation of rural groundwater supplies. Due to the greater contact times for rock-water actions in these deeper positions, the concentrations of PTEs are often higher in the groundwater (Hem, 1992). Zheng et al. (2005), for instance, found trace element concentrations of the drinking water in Bangladesh to be positively related to well depth: the deeper the well or borehole, the higher the concentrations of PTEs in the drinking water.

Table 3.47 Background Se and F concentrations of drinking water in areas with Kashin-Beck disease and fluorosis.

[Based on (1) Fordyce (2013); (2) Zhang et al. (2011); (3) Jones et al. (1977); (4) Maithani et al. (1998); (5) Edmunds & Smedley (2013)]

Area	Se	F	Ref.
	($\mu g\ L^{-1}$)	($mg\ L^{-1}$)	
Kashin-Beck-disease area in China	0.005	na	(1)
Kashin-Beck-disease area at the Tibetan Plateau	< 0.08	na	(2)
Dental-fluorosis area at Lake Naivasha, Kenya	na	> 1.7	(3)
Skeletal-fluorosis area in India	na	> 18	(4)
Skeletal-fluorosis area at Lake Magadi, Tanzania	na	> 1281	(5)

(na: not available; Ref.: reference)

However, when comparing the mineral and trace element concentrations of the surface and groundwater in the Kaduna study area, no significant differences were found. Furthermore, the pH values as well as the Ca, Se and F concentrations were more or less similar in the surface and groundwater (see Tables 3.43 and 3.44 as well as Figure 3.12). The similarity in the surface and groundwater concentrations was assumed to be caused by the overall low number of water samples, which were between 4 and 19, depending on the element that was analysed (see Appendix C). According to Garrett (2013), however, at least 30 different sites must be sampled, otherwise the statistical analyses fail or are insufficient.

In summary, the analysis of the drinking water in the Kaduna study area showed that the median pH and Ca concentrations are lower in the HR-village drinking water than in the NR-village drinking water. The Se concentrations were lowest in the LR-village and NR-village water, while F was highest in the drinking water of the LR village. Compared to northern Nigerian background levels, the pH and Ca concentrations of the drinking water in the Kaduna study area were low, while the Se concentrations were normal and the F concentrations were normal to slightly elevated. However, compared to the WHO guideline levels, the Ca concentrations of the drinking water in the Kaduna study area were high enough to guarantee sufficient supplies to humans, the Se concentrations were normal and the F concentrations were too low to have any potential detrimental effect on human health. Compared to the mineral and trace element concentrations of drinking water in areas with Kashin-Beck disease and fluorosis, the drinking water in the Kaduna study area contained marginal Se and very low F concentrations. No significant difference was found between the surface and groundwater in the Kaduna study area with regard to its element concentrations (see Figure 3.12).

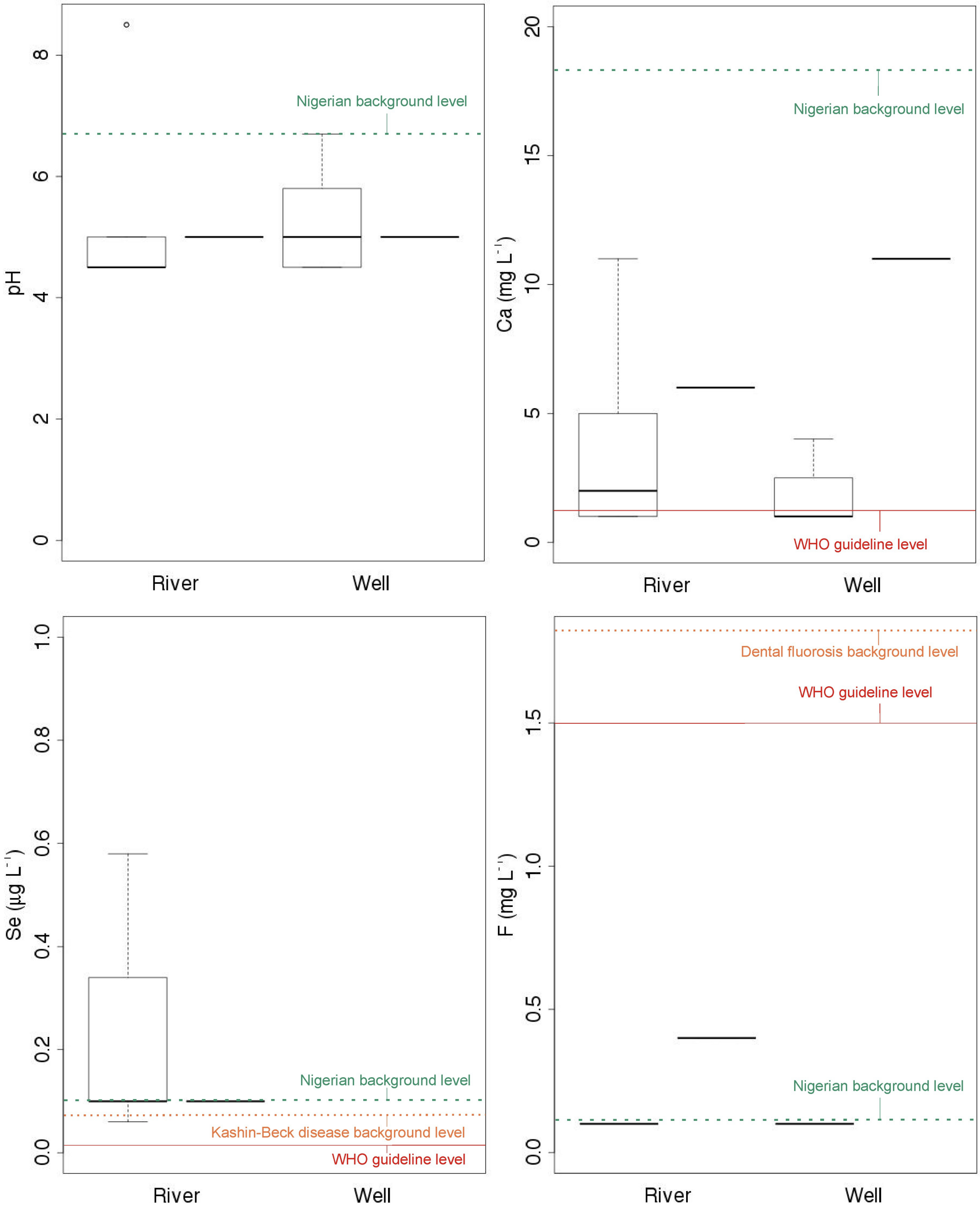

Figure 3.12 pH values as well as Ca, Se and F concentrations of surface and groundwater in the Kaduna study area compared to northern Nigerian background levels and WHO guideline levels for drinking water quality.

[The left bar of a pair represents CDR-high-risk (HR) village Kaso: CDR prevalence rate > 5%; the right pair of a bar represents CDR-low-risk (LR) village Panzato: CDR prevalence rate ≤ 5%; dashed green lines represent Nigerian background levels (as given by Anudu et al., 2011; Asubiojo et al., 1997; Jatau et al., 2008; Preez & Barber, 1965); dotted orange lines represent background levels in areas with Kashin-Beck disease and fluorosis (as given by Fordyce, 2013; Jones et al., 1977); solid red lines represent WHO guideline levels for drinking water quality (as given by WHO, 2011; 2009)]

3.6 Maize

3.6.1 Macronutrients and micronutrients

Most often, macronutrient and micronutrient deficiencies in humans are the consequence of insufficient dietary intake (Frayn & Akanji, 2006). However, the mineral and trace element deficiencies in crops are not only a consequence of low primary or secondary soil fertility (Combs, 2013; Fairweather-Tait et al., 2011; Pooley, 1997; Yang et al., 2007). Instead, parameters such as crop specie or variety also determine the content of macronutrients and micronutrients that reach humans (Graham, 1984; Peterson et al., 1986; Rengel et al., 1999). To assess the contents of nutrients reaching the local Kaduna population, maize from the Kaduna study area was analysed for Ca, Mg, K, P and Se contents.

Table 3.48 Ca, Mg, K and P contents of maize in the Kaduna study area.
Detailed data are given in Appendix D.

Study site	Maize variety	n	Ca	Mg	K	P
			Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
			(mg kg^{-1})			
HR villages	Modern	4	65.9 ± 9.9	1015.5 ± 90.5	3406.1 ± 285.4	2511.4 ± 462.8
	Traditional	2	72.0 ± 5.1	1099.1 ± 275.6	3338.7 ± 834.8	2827.7 ± 1,033.2
HR villages mean		6	68.0 ± 8.6	1043.4 ± 148.2	3379.2 ± 465.1	2616.8 ± 607.2
LR village	Modern	0	nd	nd	nd	nd
	Traditional	1	115.6	1011.0	2311.5	1725.9
LR village mean		1	115.6	1011.0	2311.5	1725.9
NR village	Modern	1	63.1	978.6	3487.5	2884.4
	Traditional	1	55.2	906.2	3436.3	1826.7
NR village mean		2	59.2 ± 5.6	942.4 ± 51.2	3461.9 ± 36.2	2355.6 ± 747.9
Study-area mean		9	71.3 ± 18.5	1017.3 ± 126.4	3266.4 ± 523.5	2459.8 ± 623.6

(n: number of samples; nd: not determined; HR villages (Kaso, Jankassa): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%; NR village (Dakala): CDR prevalence rate = 0%)

It thereby became apparent that the overall mean Ca, Mg, K and P contents of the maize in the Kaduna study area were 71.3 mg kg^{-1}, 1017.3 mg kg^{-1}, 3266.4 mg kg^{-1} and 2459.8 mg kg^{-1}, respectively. The Ca, Mg and P contents were lowest in the maize of the NR village. The Mg contents were similar in the maize from all the study sites (see Table 3.48). The Se contents of the maize in the Kaduna study area were always below 0.01 mg kg^{-1}. No difference was found between the HR, LR and NR areas with regard to the Se contents in the maize (see Table 3.49), which, however, may be due to the insensibility of the laboratory method used.

According to Bakare-Odunola et al. (2012) and Turaki (2007), who worked in the CDR villages Gonin Gora, Jankassa and Kaso near Kaduna City (see Figure 3.7), the maize in the Kaduna study area typically contains Ca and P contents of 7.0 to 68.0 mg kg^{-1} and 3100 to 3600 mg kg^{-1}, respectively. Compared to these contents, the results of this study were found to be representative for the Kaduna study area.

To check for possible anomalies in the macronutrient and micronutrient concentrations, food composition tables, providing the mean mineral contents of specific crops from specific areas, are usually taken for comparison (Greenfield & Southgate, 2003; Reuter & Robinson, 1997). For West Africa, the most recent and comprehensive food composition table was published under the aegis of the FAO (Stadlmayr et al., 2012). According to this collection, the mean Ca, Mg, K and P contents in the maize from West Africa typically are 120 to 190 mg kg^{-1}, 790 to 1230 mg kg^{-1}, 2950 to 3460 mg kg^{-1} and 2380 to 2460 mg kg^{-1}, respectively (see Table 3.50). Although lower contents of K and P were found in the maize of the LR village, these contents were interpreted as outlier, as they were significantly lower than the contents measured in all the other maize samples taken from the Kaduna study area (see Table 3.48). Compared to these contents, the mean Ca concentration of the maize in the Kaduna study area is low, while the mean Mg, K and P contents are within normal ranges. This result is in line with results of interviews with local small-scale farmers in the Kaduna study area, who stated that nutritional disorders of plants, such as chlorosis or stunted growth, are uncommon in their crop plants. Furthermore, no signs of Ca deficiency in maize, which commonly becomes apparent by serrated and curled leaves, was observed by the local farmers.

Table 3.49 Se contents of maize in the Kaduna study area.

Detailed data are given in Appendix D.

Area	n	Se Mean (mg kg^{-1})
HR villages	2	< 0.01
LR village	1	< 0.01
NR village	1	< 0.01

(HR villages (Kaso, Jankassa): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%; NR village (Dakala): CDR prevalence rate = 0%; n: number of samples)

To check if the maize in the Kaduna study area is low not only in comparison to the food composition data, but also in general, the Ca contents of the maize in the Kaduna study area were again compared to Nigerian background levels. According to Edema et al. (2005), commercially sold maize meal and the meal of quality protein maize bred by the International Institute of Tropical Agriculture in Nigeria (IITA), contain mean Ca contents of 114.7 mg kg^{-1} and 123.7 mg kg^{-1}, respectively. Olaofe and Sanni (1988) found that maize in Ilorin City contains only 22.0 mg kg^{-1} Ca, while Adeyeye and Ajewole (1992) reported that maize in Ibadan contains up to 60.0 mg kg^{-1} Ca in the grains. Frossard et al. (2000), state that the Ca content of maize in the US is around 80 mg kg^{-1}. Compared to these background values, the Ca content of the maize in the Kaduna study area was low, but not deficient. However, as comparable data from Nigeria are rare and often missing details about the laboratory method used, the environmental conditions of the growing sites and the maize variety, exact comparisons were not possible. To further determine the concentration of Ca in the maize of the Kaduna study area as well as the possible influence of dietary Ca deficiency on CDR, further analyses with increased sample numbers are needed.

With regard to Se, no data were included in the Stadlmayr (2012) food composition table. However, Sillanpää and Jansson (1992) reported that maize in West Africa typically contains Se contents of 0.2 mg kg^{-1} (see Table 3.50). In Malawi, Chilimba et al. (2011) find the Se contents in maize cultivated in Se-deficient soils to always be below 0.05 mg kg^{-1}. According to Jacobs (1989), the risk of Se deficiency in humans is high when maize as a staple food contains less than 0.025 mg kg^{-1} Se. Compared to these data, the Se contents of the maize in the Kaduna study area, which always were less than 0.01 mg kg^{-1}, were very low (see Figure 3.14).

Table 3.50 Background Ca, Mg, K, P and Se contents of West African maize as given in food composition tables.

[Based on (1) Stadlmayr et al. (2012); (2) Sillanpää & Jansson (1992)]

Maize variety	n	Ca	Mg	K	P	Se	Ref.
		(mg kg^{-1})					
Whole kernel, dried, traditional variety	2	120 ± 50	1210 ± 300	2950 ± 990	2420 ± 600	na	(1)
Whole kernel, dried, traditional variety	3	180	1230	3460	2410	na	(1)
Whole kernel, dried, traditional variety	3	190 ± 70	820 ± 100	3100 ± 700	2460 ± 300	na	(1)
Whole kernel, dried, modern TZPB-SR variety	3	180	790	3010	2380	na	(1)
Whole kernel, dried, modern Gnonli variety	3	180	800	3020	2390	na	(1)
Maize, not further specified	101	na	na	na	na	0.2 ± 0.2	(2)

(n: number of samples; na: not available; Ref.: reference)

A comparison to the critical limits reported from other bone disease areas was not possible, as only studies on nutritional behaviour were reported, but not a single study was found on crop composition. Marasas and Rensburg (1986) analysed food crops in Mseleni-joint-disease areas for fungal contamination and Zhang et al. (2011) performed similar analyses in Kashin-Beck-disease areas; they concluded that specific fungi may be involved in causing the diseases. As fungi were not analysed in this doctoral thesis, no comments can be made on this point. However, their research suggests that fungi-contamination analyses should be conducted in future studies.

Apart from the macronutrient and micronutrient contents found in specific plant species, such as maize, the mineral and trace element contents can also vary between the varieties of the same plant species (Graham, 1984; Menkir, 2008; Yang et al., 2007). According to Alloway (2013), the genotype of a plant plays a major role in the extent to which elements are accumulated in the plant tissues. Typically, modern crop varieties need higher fertilizer inputs to realise their field potential, while traditional crop varieties are adapted to the naturally low nutrient contents in tropical soils.

In the Kaduna study area, two different maize varieties were analysed for their macronutrient and micronutrient contents: modern and traditional maize. While modern maize was introduced to the Kaduna study area no earlier than the 1960s to increase yields, traditional maize has been cultivated for centuries. Nowadays, modern maize is cultivated especially by younger families, who praise its better taste and traditional maize is grown only by a small number of predominantly older farmers (see Chapter 3.3).

A comparison between the composition of modern and traditional maize varieties in the Kaduna study area showed the median Ca contents to be lower in the modern than in the traditional maize (66.3 vs. 72.0 mg kg^{-1}). In contrast, the median Mg (978.6 vs. 958.6 mg kg^{-1}), K (3481.2 vs. 3092.4 mg kg^{-1}) and P contents (2592.9 vs. 1961.9 mg kg^{-1}) were higher in the modern than in the traditional maize varieties (see Figure 3.13). This result contrasts to the food composition data presented in Table 3.51, according to which the Ca contents are typically higher in the modern than in the traditional West African maize varieties (180 mg kg^{-1} vs. 120 mg kg^{-1}) and the Mg (800 mg kg^{-1} vs. 1210 mg kg^{-1}), K (3020 mg kg^{-1} vs. 3460 mg kg^{-1}) and P contents (2390 mg kg^{-1} vs. 2460 mg kg^{-1}) are commonly lower in the modern than in the traditional West African maize varieties (Stadlmayr et al., 2012). Iken et al. (2002), however, could not find any differences between the Ca, Mg, K and P contents of modern and traditional maize from Nigeria at all. According to Bouis (2002), on the other hand, modern crop varieties are specifically bred to increase specific desired characteristics of a crop, such as higher macronutrient and micronutrient contents. Alloway (2009) stated that there are significant differences between different crop varieties in the extent to which they can tolerate macronutrient- and micronutrient-deficient soils. The differences in the Ca, Mg, K and P contents between the modern and traditional maize of the Kaduna study area are therefore, in all probability, due to differences in the variety. However, the number of samples was small. A conclusively discussion on the reason for the difference in the Ca contents of traditional and modern maize from the Kaduna study area was therefore not possible.

Furthermore, when looking at Figure 3.13, it becomes apparent that the relief or range of the macronutrient and micronutrient contents of traditional maize is much higher than that of the modern varieties, where macronutrient and micronutrient contents were always within a narrow range about a central tendency. According to Cakmak et al. (2000), who analysed traditional and modern wheat varieties in Turkey, noisy data in traditional varieties are an expression of a broader gene pool and a higher variation in macronutrient and micronutrient contents in general. Garrett (2013), in contrast, ascribes high-relief data to be a function only of different ecological growing conditions. However, to be able to estimate the impact of the higher nutrient variation in the traditional maize, further analyses are needed.

Apart from a shift from the traditional to the modern maize varieties, the small-scale farmers of the Kaduna study area also stated that nutrition in general has changed during the last decades. While in former times, sorghum was the staple crop in the region, a change to maize was noticed to have happened some decades ago. Wild animals, which had served as important macronutrient and micronutrient suppliers in the former daily diet were eradicated in the entire Kaduna study area. Meat was stated to nowadays be eaten only occasionally. The nutrient-rich wild fruit, vegetable and spice varieties were found to still grow on top of inselbergs, the former settlement areas of the local population, but were nowadays rarely used. Similar observations were made also by Emmert (2009), who studied the nutritional preferences of the local population of the Kaduna study area.

According to Fahey (2005), Frison et al. (2006), Kuhnlein and Receveur (1996), Lokkett et al. (2000), Long et al. (2011), Mibei et al. (2011) and Mebrahatu et al. (1995), such gradual losses in dietary diversity towards a one-sided, fish- and meat-free diet are at high risk of causing malnutrition in indigenous people. In particular, a shift from comparatively macronutrient- and micronutrient-rich sorghum to macronutrient- and micronutrient-poor maize can cause nutrient deficiencies in humans, independent of the environmental conditions (Broadley et al., 2012; Chilimba et al., 2011; Graham et al., 2007; Grusak, 2002).

Apart from explanations based on plants or soils, some authors have also argued that the season of pregnancy may determine the nutrient contents ingested in nutrition, thereby affecting fetal development and the child's later health (Namgung & Tsang, 2000; Watson & McDonald, 2007). From the Kaduna study area it is, for example, known that food resources become scarce at the end of the dry season, causing diets to become strongly one-sided (Emmert, 2009). Thus, it might be possible that children conceived during a specific season are at higher risk of developing early (micro-) nutrient deficiencies than children conceived during a different season. Data collection and assessing the birth months of the CDR children should easily clear this question.

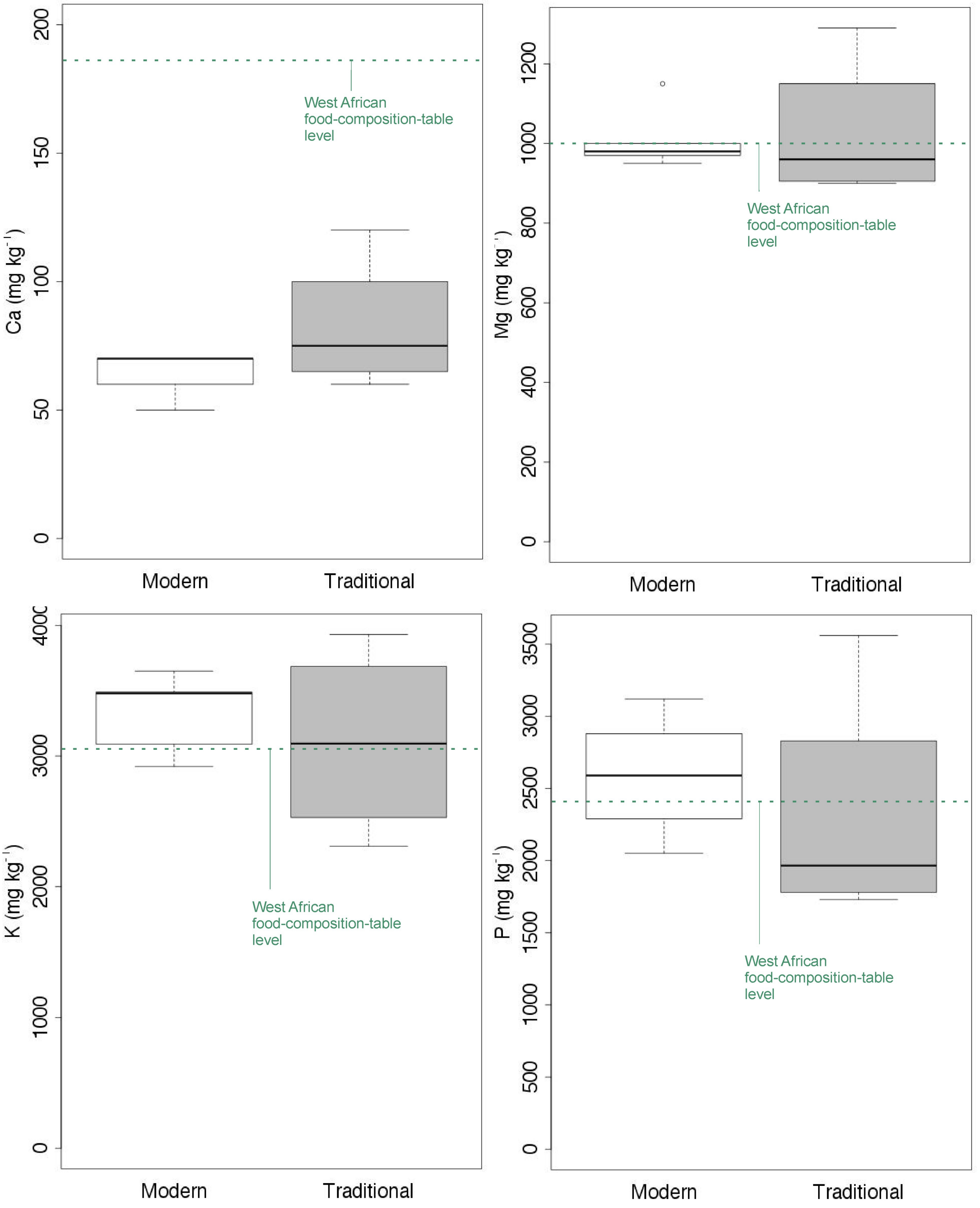

Figure 3.13 Ca, Mg, K and P contents of maize in the Kaduna study area compared to West African food-composition-table data.

[White bars represent modern maize; grey bars represent traditional maize; dashed green lines represent contents as given in a West African food composition table (Stadlmayr et al., 2012)]

In summary, the local, rural Kaduna population was found to have undergone a nutritional change during the last decades, switching from a diet based on sorghum to a (modern) maize-dominated nutrition. A lack of Ca- and micronutrient-rich food components was identified, as wild fruits and vegetables, meat and dairy products were increasingly missing in the daily diet. The macronutrient and micronutrient composition of the maize in the Kaduna study area was representative for the region. However, compared to West African and Nigerian background levels, the maize in the Kaduna study area had only marginal Ca and Se contents. The Ca contents were high only in the traditional maize varieties, which also showed the highest ranges in all the other macronutrients. The Se contents were significantly low compared to both West African and Nigerian background levels. Further analyses with an increased number of samples are required to guarantee statistical significance. In addition, analyses on possible fungal contamination of the local food crops and data collection on the birth months of the CDR children should be conducted.

3.6.2 Phytic acids

Apart from primary deficiencies due to low macronutrient and micronutrient intakes or an imbalanced diet, macronutrient and micronutrient deficiencies in humans may also occur due to the steady consumption of high contents of phytic acids (PAs), which are especially high in cereals (Knez & Graham, 2013; Schlemmer et al., 2001). PAs are chelating agents which are known to bind with macronutrient and micronutrients in the gut and consequently limit their absorption (Schlemmer et al., 2009). In rural areas of developing countries, where people largely depend on cereals and legumes in their diets, daily PA ingestion is usually higher than in cities, where most people have started to adapt to Western-type diets and animal products (Ma et al., 2007). For Africa, the mean PA intake is estimated to range between 560 to 2390 mg^{-d}, depending on country, study and methodological approach (Schlemmer et al., 2009), while in Nigeria, the average PA contents, with approximately 2200 mg^{-d}, are estimated to be relatively high (Harland et al., 1988).

In animal experiments with baboons, a one-sided, PA-rich maize nutrition was found to cause rachitic symptoms (Sly et al., 1984). The first to detect the link between increased PA consumption and rickets in children were McCance and Widdowson (1935) and McCance and Walsham (1948), who found that schoolchildren in London developed reduced Ca-absorption and rachitic bone deformities under a dairy-poor, wholemeal wheaten bread-rich diet. Also in 1940s Dublin, rickets symptoms in children were correlated with an increased ingestion of a PA-rich, cereal-based nutrition (Robertson et al., 1980). Based on this knowledge, the CDR in developing countries has often been associated to be caused by high PA contents in nutrition (Thacher et al., 2000; Wills et al., 1972).

In the Kaduna study area, the mean PA content in maize was 7462.5 ± 2002.4 mg kg^{-1}. No maize samples were taken from the LR village, thus comparisons were possible only between the HR and NR villages. The comparisons showed that the mean PA maize contents, with 9290.0 mg kg^{-1}, were the highest in the modern maize from the NR village and, with 5020.0 mg kg^{-1}, were the lowest in the traditional maize from the NR village. However, both results were based on one maize sample, which means a comparison between these two values does not necessarily provide representative results (see Table 3.51).

Finding PA background values is not easy, as PA and phytate contents are often confused in food tables (Schlemmer et al., 2009). The few data that were found for West African maize are presented in Table 3.52. According to this, the PA content in raw maize from West Africa typically ranges between 6400 and 7300 mg kg^{-1}, which is in fully agreement to the own findings, showing the mean PA contents of the maize in the Kaduna study area to be 7462.5 ± 2002.4 mg g^{-1} on average. The slight difference between the West African background value and the own results may be explained by the fact that the exact PA content of a cereal always depends on environmental conditions, the stage of seed maturation or the analytical method applied (Bürkert et al., 1998; Schlemmer et al., 2009).

Table 3.51 PA contents of maize in the Kaduna study area.

Detailed area and variety-specific data are given in Appendix D.

Study site	**Maize variety**	**n**	**PA Mean ± SD ($mg\ kg^{-1}$)**
HR villages	Modern	4	7395.0 ± 1175.7
	Traditional	2	7905.0 ± 3768.9
HR village mean		6	7565.0 ± 1933.8
LR village	Modern	0	nd
	Traditional	0	nd
LR village mean		0	nd
NR village	Modern	1	9290.0
	Traditional	1	5020.0
NR village mean		2	7155.0 ± 3019.3
Study-area mean		8	7462.5 ± 2002.4

(n: number of samples; nd: not determined; PA: phytic acid; HR village (Kaso, Jankassa): CDR prevalence rate > 5%; LR village (Panzato): CDR prevalence rate ≤ 5%; NR village (Dakala): CDR prevalence rate = 0%)

However, it should be noted that the contents of PA in raw maize do not reflect the real intake in humans, since food processing has a great impact on the PA content in food (Ayatse et al., 1983). To reduce PA contents, several methods of dephytinization have been described in literature, such as hydrothermal treatment (Egli et al., 2004), soaking maize meal in water (Akaninwor & Okechukwu, 2004; Manna et al., 1987) or malting (Larsson et al., 1996).

Table 3.52 Background PA contents of West African maize.

[Based on (1) Marfo et al. (1990); (2) Akaninwor & Okechukwu (2004)]

Maize variety	**PA ($mg\ kg^{-1}$)**	**Ref.**
White maize (Ghana), unknown variety, dried, full grain (Ghana)	7300 ± 300	(1)
Yellow maize, dried, unknown variety, full grain (Ghana)	6900 ± 100	(1)
Maize, unknown variety, dried, milled	6400	(2)

(Ref.: reference; PA: phytic acid)

Nevertheless, according to Thacher et al. (2009), the PA contents in maize porridge can significantly be reduced only by enzymatic dephytinization. In the Kaduna study area, where the local maize porridge (*tuwo*) is commonly prepared after graining and cooking in hot water (Abdulrahaman & Kolawole, 2006), the PA contents were assumed to still be considerably high in the meals of the Kaduna study area. However, according to Adams et al. (2002) and Thacher et al. (2009), the regular consumption of PA-rich maize porridge affects Zn but not Ca absorption. Similar findings were also reported by Reinhold (1971) and Reinhold et al. (1979), who found parts of the rural Iranian population to suffer from Zn deficiency and growth retardation due to the one-sided consumption of PA-rich wheat bread.

Whether the CDR children in the Kaduna study area have likewise a Zn deficiency has yet not been analysed.

During the last decades and with increasing public awareness on the antinutritive effect of PA, modern, low-phytic-acid maize lines have been bred, containing PA contents of less than 2700 mg kg^{-1} (Adams et al., 2002). In modern maize, the PA contents are therefore much less than the PA contents in traditional ones, which usually contain PA contents between 7000 and 10000 mg kg^{-1} (Raboy, 2000). Having low PA contents in modern maize stands in contrast to the results of this study, according to which the median PA contents were found to be higher in the modern maize than in the traditional maize varieties of the Kaduna study area (7710 vs. 5240 mg kg^{-1}) (see Figure 3.14). Although the cause of this difference was not detectable, the results may suggest that a shift from traditional to modern maize varieties may have brought about an increase in PA intake. However, the number of samples was found to be too small to allow a representative data interpretation. Further analyses should therefore include a higher number of samples.

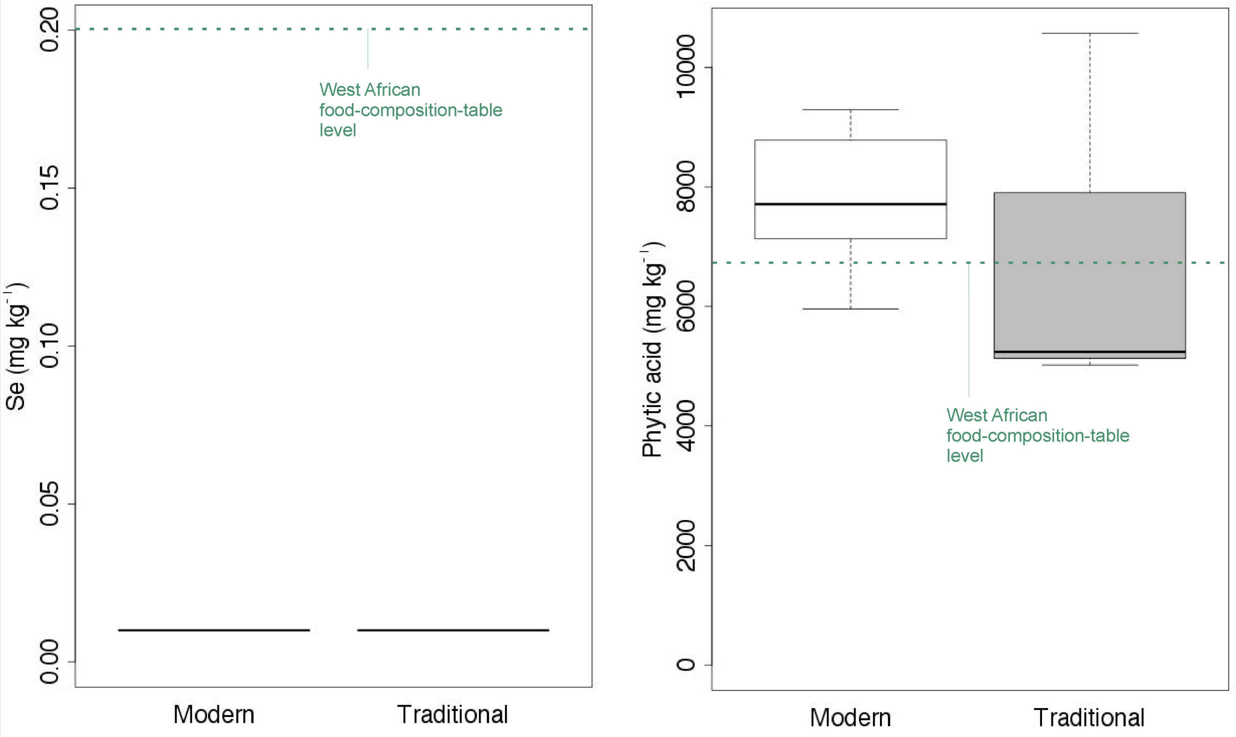

Figure 3.14 Se and PA contents of maize in the Kaduna study area compared to West African food-composition-table data.

[White bars represent modern maize; grey bars represent traditional maize; dashed green lines represent West African food-composition-table values (as given by Marfo et al., 1990; Sillanpää & Jansson, 1992)]

To sum up, the maize in the HR village of the Kaduna study area contained higher contents of PA than the maize in the NR village. Compared to West African food composition tables, the maize in the Kaduna study area had slightly elevated PA contents. A comparison between the modern and traditional maize varieties showed higher PA contents in the modern maize than in the traditional maize, which may play a role in differences in Ca absorption in children living at these two study sites.

3.7 Environmental conditions of other calcium-deficiency-rickets areas

Cases of CDR have not only been reported from the Kaduna study area, but have also been reported from other areas in Nigeria and even other developing countries over the last 30 years. Clear differential diagnoses in favour of CDR are known from different areas in Bangladesh, South Africa and The Gambia. These areas include the Chittagong, Jessore and Sylhet districts in Bangladesh (Arnaud et al., 2007; Combs & Hassan, 2005; Combs et al., 2008; Craviari et al., 2008; Fischer et al., 1999), the Kwoi Local Government area and the Kachia Local Government area in Nigeria (HVCF, unpublished, 2013), the Jos Local Government area in Nigeria (Fischer et al., 2000; Graff et al., 2004; Keating et al., 2011; Oramasionwu et al., 2008; Pfitzner et al., 2001; 1998; Thacher et al., 2009; 2002; 2000; 1999; VanderJagt et al., 2001; Wright et al., 2005), the Gert Sibande District (Mpumalanga Province) in South Africa (Pettifor et al., 1981; 1979; 1978) and the Kiang West District in The Gambia (Braithwaite et al., 2011; Jones et al., 2009; Prentice, 2013; Prentice et al., 2008; 2006) (see Chapter 2.6).

In the Chittagong District, the Jos Local Government area and the Kiang West District, CDR prevalence rates were 8.7% (Kabir, 1998; Kabir et al., 2004), 9.0% (Pfitzner et al., 1998) and less than 0.6% (Jones et al., 2009), respectively. In the Gert Sibande District, approximately 13% of the paediatric population had hypocalcaemia (Pettifor et al., 1981). For the other districts and areas, no prevalence statistics are available (see Chapter 2.6).

As research trips to these areas were not possible (see Chapter 2.1), the environmental conditions of these CDR areas were analysed by a literature review. This literature review was made to verify the research results from the Kaduna study area. Results gained by this literature review should be considered with care and do not replace the accuracy of field-based research results.

3.7.1 Bedrock and parent materials

The bedrock and parent materials of other CDR-affected areas within developing countries were highly diverse, were differing not only in ages, ranging from as old as Archean and as young as Holocene, but were also greatly differing in the type of bedrock and parent material, including potentially macronutrient- and micronutrient-poor bedrock, such as sandstone as well as bedrock and parent-material types that are rich in macronutrients and micronutrients, such as basalt or alluvial deposits.

In the Chittagong Division, the dominant parent materials are Quaternary dune and beach sands as well as alluvial deposits. In the western Jessore District, deltaic deposits of various ages have deposited. The northern Sylhet and Sunamganj Districts are dominated by Quaternary alluvial deposits, marsh clay and peat (Kinniburgh & Smedley, 2001). In the area around Kachia in Nigeria, the common bedrock is migmatite-gneiss complex, while in the Kwoi Local Government area, mainly schists are found which are covered by slope deposits (Kaduna State Geological Survey, 2008). Depending on the slope position, ferricrete-originated slope deposits, river and aeolian deposits are found (Wall, 1979). According to the Land Resource Study of the Jos Plateau (Hill, 1978), the Jos area is geologically composed of medium- to coarse-grained, alkaline, biotite-rich Younger Granites of Jurassic age, Tertiary basalts and Pliocene ferricretes which are covered by slope deposits (Zeese et al., 1994). Furthermore, river deposits as well as yellowish, loamy aeolian deposits of various younger ages can be found near Jos City (Hill, 1978; Obaje, 2009). In the CDR areas of South Africa, the dominant parent materials are slope deposits covering Archean, medium- to coarse-grained, biotite-rich crystalline basement granites (Turner, 2000). In the Kiang West District in The Gambia, the main parent materials are Tertiary sandstone and Pliocene ferricretes as well as river deposits of various younger ages (Jarrett, 1949; Schlüter, 2006) (see Table 3.53).

Table 3.53 Parent materials of other CDR areas within developing countries.

[Based on (1) FAO (1988); Kinniburgh & Smedley (2001); (2) Kaduna State Geological Survey (2008); Wall (1979); (3) Hill (1978); Obaje (2009); (4) Turner (2000); (5) Jarrett (1949); Schlüter (2006)]

Country	District/ Local Government	Parent materials	Ref.
Bangladesh	Chittagong	Quaternary beach and dune sand, alluvial deposits	(1)
	Jessore	Deltaic deposits of various ages	(1)
	Sylhet	Quaternary alluvial deposits, marsh clay and peat	(1)
Nigeria	Kwoi, Kachia	Slope deposits over Paleoproterozoic migmatite-gneiss complex, Neoproterozoic metasediments (schist) and Pliocene ferricretes as well as river and aeolian deposits of various ages	(2)
	Jos	Slope deposits over Jurassic Younger Granites, Tertiary basalts and Pliocene ferricretes as well as river and aeolian deposits of various ages	(3)
South Africa	Gert Sibande	Slope deposits over Archean biotite granite	(4)
The Gambia	Kiang West	Slope deposits over Tertiary sandstone and Pliocene ferricrete as well as river deposits of various ages	(5)

(Ref.: reference)

The different bedrocks and parent materials of the above mentioned CDR areas were highly diverse with regard to types, potential geochemical composition and ages. No common pattern of distribution was identified. In Nigeria, the CDR areas around Kaduna City, Kachia City Kwoi City and Jos City were underlain by different parent materials, which disproves the assumption that CDR might be restricted to Older-Granite areas (see Chapter 3.1).

Furthermore, the assumption that CDR areas may be restricted to areas of old, infertile geological bedrock could not be confirmed. Soils that have developed on deltaic or alluvial deposits in Bangladesh are known to be rich sources of macronutrients and micronutrients (Huq & Shoaib, 2013). In the Jos Local Government area, which is underlain by Jurassic Younger Granites and Tertiary basalts, high concentrations of macronutrients and micronutrients are to be expected in the soils and environment (Obaje, 2009). A direct link of CDR cases to areas of macronutrient- and micronutrient-poor bedrock is therefore unlikely.

Apart from that, no similarity was found with regard to the nutrient and PTE concentrations of the different bedrock and parent materials in tropical CDR areas. Although migmatite-gneiss complex bedrock in the Kwoi and Kachia local government areas, biotite-rich Younger Granites in the Jos Local Government area and biotite-rich granites in the Gert Sibande District may contain higher concentrations of F (see Chapter 3.1), groundwater analyses in the CDR areas in Bangladesh, Nigeria and South Africa indicate that F is not elevated in the drinking water of these areas (Pettifor et al., 2008). Low concentrations of F, deriving from bedrock to drinking water, were also found in the drinking water of the Kaduna study area (see Chapter 3.5).

In summary, the bedrock and parent materials of other CDR areas within developing countries were highly diverse with regard to geochemical composition and geological ages.

Neither a marked bedrock-deriving macronutrient or micronutrient deficiency, nor a specific bedrock-deriving trace element-oversupply was identified in the soils of the different CDR areas. A direct link between CDR and bedrock or parent materials, producing naturally low macronutrient and micronutrient concentrations or PTE oversupplies is therefore unlikely.

3.7.2 Land use

In Bangladesh, most of the land surface of the Chittagong, Jessore and Sylhet districts is used for commercial rice cultivation. In urban CDR areas in Bangladesh, diverse industrial complexes are found (Ali et al., 1997). According to Huq and Shoaib (2013), the population is steadily increasing in these regions of Bangladesh, which poses a potential anthropogenic stress to the local ecosystems. Most of the CDR-affected villages in Nigeria, around the Kwoi and Kachia local government areas are found in rural areas (HVCF, unpublished, 2013). The landscape near Kwoi and Kachia is agriculturally used with the cultivation of both food and cash crops (Wall, 1979). The Jos Local Government area is under intensive agricultural use and maize is grown as a staple food, while vegetables, cassava and groundnuts are grown as cash crops. The cases of CDR in Nigeria are not limited to rural areas only, but are also found in Jos City (Combs & Hassan, 2008; Pfitzner et al., 1998), an area which is dominated by urban activities and which was once an important centre of tin mining (Hill, 1978). According to Anthony (2009), the population growth in Nigeria is immense and even exceeds that of agricultural production. In the Gert Sibande District in South Africa, citrus and exotic fruits are grown as cash crops. Additionally, livestock and timber production as well as urban activities are found (DARDLA, 2005). The cases of CDR in South Africa are typically restricted to rural areas, with the parents of the CDR-affected children living on subsistence farming (Pettifor et al., 1978; 1997). According to Kimuna and Makiwane (2007), the population growth of the Gert Sibande District in South Africa is one of the highest in the country. The Kiang West District in The Gambia is a mostly rural area, where groundnuts are grown as cash crops (McGregor & Smith, 1952) (see Table 3.54). No clear data on the population growth rates in the Kiang West District were found.

Comparing the different CDR areas to each other, one becomes aware that the cases of CDR are found in both rural and urban areas. While urban areas are known to often be polluted with PTEs derived from industrial sources (Awomeso et al., 2010; McMichael, 2000; Yabe et al., 2010; Zessa & Tasciotti, 2010), rural areas are most often affected by the consequences of intensified land use, which is usually accompanied by a loss of soil fertility or an increase of PTEs in soil (Foley et al., 2005; Lal, 2009).

An example for an urban CDR area is Jos City, where the CDR prevalence rates were reported to be even higher than those of the rural surrounding (Pfitzner et al., 1998). Analyses on the serum of CDR children living in Jos City showed significantly elevated Pb concentrations (Pfitzner et al., 2001), which led Keating et al. (2011) to assume that the differences in the urban versus rural CDR prevalence rates are influenced by environmental Pb poisoning. High Pb concentrations in northern Nigeria have often been associated with informal gold mining activities (Plumlee et al., 2013), but CDR children from Jos City were not found to live or work near artisanal gold mines (Keating et al., 2011). Instead, Wright et al. (2005) found children living near a gasoline-seller or battery smelter or using lead-ore eye cosmetics to be at the highest risk for CDR. Furthermore, increased Pb exposure often was found to be linked to low socio-economic status (Mathee et al., 2002). However, Pb poisoning, industrial pollution and low socio-economic conditions are widespread in so many urban areas in developing countries (Awomeso et al., 2010; Ene-Obong et al., 2001; Jatau et al., 2008; McMichael, 2000; Oluwatosin et al., 2008) in which there are no reported cases of CDR. A general link between industrial pollution and CDR therefore has to be questioned.

Table 3.54 Land use in other CDR areas within developing countries.
[Based on (1) Ali et al. (1997); (2) Wall (1979); (3) Hill (1978); (4) DARDLA (2005); (5) McGregor & Smith (1952)]

Country	District/ Local Government	Land use	Ref.
Bangladesh	Chittagong	Food and cash-crop production (mainly rice), urban and industrial activities	(1)
	Jessore	Food and cash-crop production (mainly rice), urban and industrial activities	(1)
	Sylhet	Food and cash-crop production (mainly rice), urban and industrial activities	(1)
Nigeria	Kwoi, Kachia	Food (maize, sorghum) and cash-crop production (ginger, groundnuts), urban activities	(2)
	Jos	Food and cash-crop production (Maize, vegetables, cassava, groundnuts), urban activities, tin mining	(3)
South Africa	Gert Sibande	Cash-crop production (citrus and exotic fruits), livestock production, urban activities, timber industry	(4)
The Gambia	Kiang West	Cash-crop production (mainly groundnuts and rice)	(5)

(Ref.: reference)

Where CDR was found in rural areas of developing countries, agriculture was identified to be the main line of business, while the crop production was to an increasing extent based on cash-crop farming. Craviari et al. (2008) reported of a clear and rapid increase in commercial rice production in the Chakaria area, Bangladesh, over the last few decades, forcing farmers to increasingly abandon traditional land-use techniques. According to Huq and Shoaib (2013) and Islam (2008), the land-use intensification in Bangladesh has led to a significant decrease in soil fertility. From The Gambia, a clear decrease in soil fertility has been reported since the 1960s (Baker, 1995; McGregor & Smith, 1952; Webb, 1992; Weil, 1986). According to Baker (1995), small-scale farmers in The Gambia were aware of over-cultivating the land, but were often too short of money and too short of labour to sustainably improve the fertility of their fields (see Chapter 3.3). However, a decrease in soil health due to agricultural overuse is clearly not a condition restricted to CDR areas, but is found all over the world and especially in developing countries (Bilsborrow, 1992; Lal, 2009; Nabhan, 2000a).

In summary, cases of CDR are typically found in urban and rural areas. In the urban areas of Jos City, for instance, CDR has been associated with increased industrial activities and Pb poisoning. In rural CDR areas, farmers were found to rely to an increasing extent on cash-crop production, which may have forced an anthropogenically driven loss of soil fertility and an increase in PTEs in soils. However, since both trace-element toxicity and macronutrient or micronutrient deficiency are of environmental concern in so many other non-CDR areas, their direct influence on CDR was questioned.

3.7.3 Soils

3.7.3.1 Types and distribution

According to the Land Resource Study of Bangladesh (FAO, 1988), the topography of the coastal areas of the Chittagong Division are dominated by river and tidal floodplains, providing a home for potentially fertile soil types, such as Gleysols, Fluvisols and Alisols. The western Jessore District in Bangladesh is located in the floodplains of the Ganges River (Kinniburgh & Smedley, 2001), where mainly Gleysols and Cambisols have developed. The northern Sylhet and Sunamganj districts in Bangladesh are located on the floodplains of rivers that enter the country from the northern and eastern hills. The dominant soil types in this region are Gleysols (FAO, 1988). According to FAO (1988), most of the Bangladeshi soils are relatively young, ranging in age from recent to several thousand of years. In Nigeria, specifically in the area around the Kwoi and Kachia local government areas, the entire landscape is characterized by undulating plains, while inselbergs are very common and ironstone-capped plateaus occur in many places (Smith, 1981; Wall, 1979). According to the evaluation of a soil map (Sonneveld, 1996), Lixisols are the main soil type in the areas around Kwoi and Kachia local governments. According to the Land Resource Studies of the Jos Plateau (Hill, 1978), the topography of the area around Jos City is characterized by gently undulating terrain, while to the north, the city is bordered by the dissected edges of the Jos Plateau's hill masses, which rise to over 1500 m AMSL. According to Sonneveld (1996), Acrisols and Cambisols are the typical soil types around Jos City. In the CDR areas in South Africa, the topography of the landscape is dominated by moderately undulating plains with gentle slopes and Lithosols as the most common soil type (Tuner, 2000). The Kiang West District in The Gambia is topographically dominated by mangrove plains, river valleys, swamps and ironstone-capped plateaus (McGregor & Smith, 1952). Mostly Fluvisols, Gleysols, Arenosols, Lithosols and Regosols are found (Giglioli & Thornton, 1965) (see Table 3.55).

Table 3.55 Topography and soil types of other CDR areas within developing countries.

[Based on (1) FAO (1988); Kinniburgh & Smedley (2001); (2) Wall (1979); Sonneveld (1996); (3) Hill (1978); Sonneveld (1996); (4) Turner (2000); (5) McGregor & Smith (1952); Giglioli & Thornton (1965)]

Country	District/ Local Government	Topography	Soil types	Ref.
Bangladesh	Chittagong	River and tidal floodplains	Alisols, Fluvisols, Gleysols...	(1)
	Jessore	High Ganges River floodplain	Cambisols, Gleysols...	(1)
	Sylhet	Surma-Kusiyara floodplain	Gleysols	(1)
Nigeria	Kwoi, Kachia	Gently undulating plains, inselbergs, scattered ironstone-capped plateaus	Lixisols, Gleysols...	(2)
	Jos	Gently undulating terrain, dissected edges, hill masses in farer distance	Acrisols, Cambisols, Gleysols...	(3)
South Africa	Gert Sibande	Moderately undulating plains, Lowveld	Lithosols...	(4)
The Gambia	Kiang West	Mangrove plains, river valleys, swamps, iron-stone capped plateaus	Fluvisols, Arenosols, Lithosols, Regosols, Gleysols	(5)

(Ref.: reference)

Comparisons between the different CDR areas showed that all the regions were located in plain lowlands. None of the areas was situated in a hilly region. Due to their easy accessibility, the plain areas are often highly agriculturally used (O'Kelly, 2007) and, where deltaic or alluvial deposits are the dominant parent material the oils are fertile (Huq & Shoaib, 2013; Young, 1976). A clear agrarian-oriented land use was identified in all the CDR areas discussed in this study (see Chapter 3.7.2).

The soil types that have developed in the plain, agriculturally-used CDR areas were highly diverse. In all the CDR areas, wetland soils, such as Gleysols or Fluvisols, were found. While these alluvial soils make up around 2% of all the soils in Africa, Gleysols and Fluvisol certainly cover a greater proportion of tropical Asia, where they have, due their high fertility, supported high population densities for many centuries (Young, 1976). Among the group of terrestrial soils that were listed in Table 3.55, the soils of potentially high fertility, such as Cambisols or Alisols as well as soils with minor physicochemical characteristics, such as Lithosols or Arenosols, were found. Low soil fertility is therefore assumed to be unlikely to be a major predisposing factor to CDR, otherwise one would expect the soils in the CDR areas to be deficient in general.

In summary, all the CDR areas were located in relatively plain areas, which were predominantly agriculturally used. No consistent pattern of soil-type distribution was found between the different areas and countries, as soil types of potentially low and soil types of potentially high soil fertility were found in close vicinity to each other. A link between soil types and CDR in other developing countries was therefore assumed to be unlikely.

3.7.3.2 Physical and chemical characteristics

In the CDR areas of Bangladesh, all the soils are dominated by a loamy to clayey texture. In Chittagong, the soils are calcareous throughout the profile, imperfectly drained and have a high CECpot and BS. The soils of the Jessore area in Bangladesh are neutral to acidic, have calcareous topsoils and a high CECpot. Around Sylhet, the soils are non-calcareous and strongly acid in the topsoils (FAO, 1988; Huq & Shoaib, 2013). In Nigeria, the soils around Kwoi and Kachia have textures dominated by sand, loamy sand and sandy loam, while the subsoils are sandy to loamy and sometimes gravelly. All the soils in the Kwoi and Kachia area are deep to very deep and well drained (FDALR, 1990). The dominant clay mineral in the soils is kaolinite. The soil fertility is moderate to low, with pH values between 5 and 6. The nutrient concentrations are generally moderate, only the P concentrations are very low (Wall, 1979). At the Jos Plateau, the soils have loamy sand to sandy loam surfaces over sandy clay loam to sandy clay subsoils. Soils that have developed directly on the bedrock are often shallow, while those found on the hill deposits are deep (Hill, 1978). All the soils are well drained (FDALR, 1990). The soils found in the Jos Local Government area have a moderate to low soil fertility, with a CECpot of less than 8 cmol kg^{-1} and pH values frequently below 5 (Hill, 1978). In the Gert Sibande District in South Africa, soils have a predominantly clayey to sandy texture, with most soils having a shallow depth and kaolinite as the dominant clay mineral (Turner, 2000). The soil fertility is moderate to low, with a CECpot often less than 8 cmol kg^{-1} and pH values between 5 and 6 (Rensburg et al., 2009). In the Kiang West District in The Gambia, the soils found near the swamps and rivers are clayey in texture, but have high contents of silt in the topsoils. In the uplands, the soils are mostly sandy. All the soils are deep with those soils found near the swamps and rivers sometimes being poorly drained (Giglioli & Thornton, 1965). The soils are dominated by high contents of kaolinite (Marius, 1982), have high concentrations of OC at greater than 5% (Giglioli & Thornton, 1965) and are relatively acidic with mean pH values of greater than 4.5 (Giglioli & King, 1966; Thornton & Giglioli, 1965). The concentrations of the plant-available Ca, K and micronutrients of the soils in the Kiang West District in The Gambia are low (Marius, 1982) (see Table 3.56).

With regard to the physical soil conditions, mostly different soil textures were found between the different soils and areas, ranging from sandy, to sandy loam, to sandy clay, to loamy sand, to sandy clay loam, to loamy to clayey textures. This diversity suggests that the physical soil parameters in CDR areas are too diverse to be a predisposing factor for CDR in developing countries.

Table 3.56 Physicochemical soil characteristics of other CDR areas within developing countries.
[Based on (1) FAO (1988); Huq & Shoaib (2013); (2) FDALR (1990); Wall (1979); (3) FDALR (1990); Hill (1978); Pfitzner et al. (2001); (4) Rensburg et al. (2009); Turner (2000); (5) Marius (1982); Giglioli & King (1966); Giglioli & Thornton (1965); Thornton & Giglioli (1965)]

Country	District/ Local Government	Physical characteristics	Chemical characteristics	Ref.
Bangladesh	Chittagong	Loamy to clayey in texture	Calcareous throughout the profile, imperfectly drained, high CECpot and BS	(1)
	Jessore	Loamy to clayey in texture	Acidic, calcareous topsoils, high CECpot	(1)
	Sylhet	Loamy to clayey in texture	Strongly acidic topsoils, non calcareous, high OC concentrations	(1)
Nigeria	Kwoi, Kachia	Sand, loamy sand to sandy loam surfaces over sandy loam to and sandy clay loam, sometimes gravelly subsoils, deep to very deep, well drained, rich in kaolinite	Moderate to low soil fertility, pH values 5-6, all nutrients in sufficient quantities except P	(2)
	Jos	Loamy sand to sandy loam surfaces over sandy clay loam to sandy clay subsoils, shallow on bedrock and ferricretes, deep on hill deposits, well drained	Moderate to low soil fertility, CECpot < 8 cmol kg^{-1}, pH < 5, high Pb concentrations (> 71 mg kg^{-1})	(3)
South Africa	Gert Sibande	Clay to sandy clay soils with low silt contents, rich in kaolinite, shallow	Moderate to low soil fertility, CECpot < 8 cmol kg^{-1}, pH 5-6	(4)
The Gambia	Kiang West	Clayey near the swaps, sandy in the uplands, deep, partially poorly drained, rich in kaolinite	Very high concentrations of OC, acidic soil conditions, low concentrations of Ca, K and micronutrients	(5)

(Ref.: reference)

Comparisons between the soil macronutrient concentrations showed that the soils in African CDR areas have a moderate to low soil fertility, while the soils in the Bangladeshi CDR areas have a relatively high CECpot and BS. In the Chittagong and Jessore districts in Bangladesh, the soils contained high Ca concentrations, which raises the question about the role of soil Ca deficiency in CDR aetiology. Data on micronutrient contents of soils in CDR areas within developing countries were rare. Further analyses are needed to assess the impact of micronutrient deficiencies on the prevalence of CDR in developing countries. As the only, more or less unique characteristic, all the CDR areas showed low soil pH values, which may have an influence on element availability and element interdependencies of the nutrient concentrations.

However, one may criticise that most of the literature used for approximating the macronutrient contents of soils in the African CDR areas was published between the 1950s and 1980s and that soil fertility has degraded since then. According to Mortimore et al. (1990), reanalysis at the former Land Resource Study research sites in the Kano area, northern Nigeria (Wall, 1979), showed that no significant change had occurred in soil physical and chemical parameters. Similar findings were also made by Harris (1998), Hoffmann et al. (2001) and Phillips-Howard and Lyon (1994), who stated that the maintenance of the soil health is the prime objective of the small-scale farmer management and that the utmost is done to sustain soil fertility. This finding stands in contrast to papers published by other authors, such as Bilsborrow (1992), Lal (2009) and Nabhan (2000a), who stated that the soil fertility in most African countries has significantly decreased during the last decades. Further analysis and long-term data on the productive performance of small-scale farming systems under climatic and demographic stress is needed to evaluate the extent of soil degradation in the different CDR areas within developing countries.

With regard to the concentrations of PTEs, no clear data were found for soils, except for one study by Pfitzner et al. (2001), who described the Pb concentrations of the soils in Jos City to be significantly elevated. Further analyses of the same authors on the serum of CDR and non-CDR children showed that in urban areas both CDR and non-CDR children had elevated Pb serum concentrations, while children in rural areas had normal Pb serum concentrations. According to Keating et al. (2011) and Wright et al. (2005), the Pb serum levels were especially high in children living near a gasoline-seller or battery smelter or who used Pb-ore eye cosmetics. However, medical analyses in the CDR areas of Bangladesh, which were mostly performed in rural areas, found no differences in the blood levels of 20 trace elements and heavy metals between cases and controls (Fischer et al., 1999). Cimma et al. (2004), who analysed Bangladeshi CDR children for Al serum levels, found Al to be within normal ranges. The elevated Pb concentrations, which had been described by Pfitzner et al. (2001), were therefore thought to be an expression of the urban environment in which CDR children were born and raised and not a unique CDR characteristic.

In summary, the soils of different CDR areas in Africa had a low soil fertility and were sandy to clayey in texture. In contrast, the soils in Bangladesh were relatively fertile and mostly clayey or loamy in texture. PTE toxicities in soils were unlikely, as serum analyses revealed the trace element levels in CDR children of Bangladesh to be generally low. Further on-site analyses on macronutrient and micronutrient availability in soils are recommended to better understand the relationship between macronutrient and micronutrient concentrations in soils and humans in the different CDR areas within developing countries.

3.7.4 Drinking water

In Bangladesh, the groundwater from the Chittagong District has low concentrations of Ca, Mg, K and P as well as high concentrations of Fe and Sr compared to Bangladesh background levels (UNICEF, 2011). Furthermore, compared to the WHO guideline levels for drinking water quality (WHO, 2011), F is low in the drinking water from the Chittagong area. In Jessore District, the groundwater is low in K, Fe and P and is normal in Ca, Mg and Sr compared to Bangladeshi background levels (UNICEF, 2011). Furthermore, compared to the WHO guideline levels (WHO, 2011), F is low in the drinking water from the Jessore area. Around Sylhet, the groundwater has low concentrations of Ca, Mg and K and has normal concentrations of P, Sr and Fe compared to Bangladeshi background levels (UNICEF, 2011). Compared to the WHO guideline levels (WHO, 2011), the F concentrations in CDR areas in Bangladesh are low. In Nigeria, Preez and Barber (1965) found groundwater to be of generally good quality in the areas around Kwoi, Kachia and Jos local governments. In the Kwoi and Kachia local government areas, the concentrations of Ca are high and the F and Fe concentrations are generally low compared to national background levels (Preez & Barber, 1965). In the Jos Local Government area, the groundwater contains normal to high concentrations of Ca and Mg and low concentrations of F compared to Nigerian background levels (Preez & Barber, 1965). Furthermore, compared to the WHO guideline levels, F concentrations in the drinking water of Jos are low (WHO, 2011). The chemical parameters of the groundwater in the Gert Sibande District, South Africa are within safe limits compared to

South African critical limits of drinking water quality, except for Ca and Mg, which are often elevated (Mpenyana-Monyatsi et al. (2012). In the Kiang West District, The Gambia, cations as well as F concentrations are generally low in the surface and groundwater (Jordan et al., 2008; Meybeck et al., 1987) (see Table 3.57).

Table 3.57 Drinking water chemistry in other CDR areas within developing countries.
[Based on (1) UNICEF (2011); (2) Preez & Barber (1965); (3) Mpenyana-Monyatsi et al. (2012); Pettifor et al. (2008); (4) Jordan et al. (2008); Meybeck et al. (1987)]

Country	District/ Local Government	Drinking water chemistry	Ref.
Bangladesh	Chittagong	Low Ca concentrations^{back}; normal Mg, K and P concentrations^{back}; high Fe and Sr concentrations^{back}; low F concentrations^{WHO}	(1)
	Jessore	Low K, Fe and P concentrations^{back}; normal Ca and Mg concentrations^{back}; high Sr concentrations^{back}; low F concentrations^{WHO}	(1)
	Sylhet	Low Ca, Mg and K concentrations^{back}; normal P and Sr concentrations^{back}; high Fe concentrations^{back}; low F concentrations^{WHO}	(1)
Nigeria	Kwoi, Kachia	High Ca and nitrates concentrations^{back}; low F concentrations^{back}; low F concentrations^{WHO}	(2)
	Jos	Normal Ca, Mg concentrations^{back}; low F concentrations^{WHO}	(2)
South Africa	Gert Sibande	High Ca, Mg and nitrates concentrations^{back}; low F concentrations^{WHO}	(3)
The Gambia	Kiang West	Low cation concentrations^{back}; very low F concentrations^{WHO}	(4)

[^{back}: compared to background levels of the respective country, ^{WHO}: compared to WHO guideline levels for drinking water quality (WHO, 2011); Ref.: reference]

According to these results, all the elements in the drinking water from the different areas and countries were found in greatly varying concentrations: for example, while Ca is low in the drinking water from the Chittagong area, Jessore typically has normal Ca concentrations in the drinking water and in the Kwoi and Kachia local government areas, Ca concentrations are even high compared to the country background levels. This was found to be true for all the macronutrients and was also confirmed by Welch et al. (1998), who found the Ca concentrations of the drinking water in the Bangladeshi CDR areas to be within normal ranges.

Furthermore, none of the PTEs was found to exceed critical limits. A fact that has also been described by Welch et al. (1998), who analysed drinking water from Chakaria, Bangladesh and always found the concentrations of Al, Pb and Sr to be within safe limits. Additionally, according to Pettifor et al. (2008), the F concentrations in drinking water are low in all the CDR areas described in this study (see Table 3.58).

Table 3.58 F concentrations of drinking water in other CDR areas within developing countries.
[Based on Pettifor et al. (2008)]

Country	District/ Local Government	F
		(mg L^{-1})
Bangladesh	Chakaria	Undetectable to 0.5
Nigeria	Jos	Undetectable to very low
South Africa	Gert Sibande	0.05-0.1

Cimma et al. (2004), who assumed that the first CDR cases in Bangladesh were correlated to the introduction of aluminium pots, replacing clay pots, found the Al serum levels of the CDR children of Bangladesh to be within normal range and concluded that the role of Al in CDR aetiology is, in all probability, insignificant.

In summary, significantly decreased macronutrient and micronutrient concentrations as well as significantly elevated PTE concentrations were not found in the drinking water of the CDR areas within developing countries, a link between nutrient deficiency or PTE oversupply in the drinking water and CDR disease in humans was therefore considered unlikely.

3.7.5 Food

With regard to the food quality in the different CDR areas within developing countries, precise scientific literature describing the concentrations of macronutrients, micronutrients as well as PTEs in local food crops is rare or almost non-existent. Only one conference abstract of Welch et al. (1998) was found, according to which the Pb, Cd, Zn, P, K, Mg, Fe, Al and Sr concentrations of rice in the CDR area of Chakaria in Bangladesh are within safe ranges compared to Bangladeshi food composition tables. Only amaranth and shrimp, which are minor food components in these areas, were high concentrations of almost all elements found. Welch et al. (1998) concluded their study by claiming to have found neither significantly decreased macronutrient or micronutrient concentrations, nor significantly increased PTE concentrations in food.

However, Welch et al. (1998) described the local nutrition to be one-sidedly based on products which are generally low in Ca. Furthermore, Combs and Hassan (2005) and Craviari et al. (2008) stated that in Bangladesh, such dietary changes towards an extremely one-sided diet have especially increased during the last decades. According to Pettifor (2004), also in CDR areas in South Africa, the nutrition is cereal-based, has little variety and hardly contains milk products. Similar conditions are also known from the Kiang West District in The Gambia, where local diets are based on rice, combined with baobab-leaf-based sauces (Prentice et al., 1993). Meat was identified to be increasingly missing in the daily diet of CDR children in developing countries, which may have further aggravated (micro-)nutrient deficiencies (Bwibo & Neumann, 2003; Combs & Hassan, 2005; Dunnigan et al., 2005).

Apart from a dietary change, causing diets to be extremely one-sided, the nutrition in CDR areas was found to be increasingly based on modern crop varieties. In CDR areas in The Gambia, for instance, modern rice varieties were introduced between the 1970s and 1980s as an answer to repeated drought events in previous years (Baker, 1995). In the Chakaria CDR area in Bangladesh, modern varieties of winter rice were introduced as a new staple food (Welch et al., 1998). However, no analyses were made on the macronutrient and micronutrient concentrations of both traditional and modern rice varieties in The Gambia. To see if there is a difference with regard to nutrient composition of traditional and modern crop varieties, further analyses are recommended.

Although most people living in CDR areas within developing countries were found to live on subsistence farming, in the CDR area in The Gambia, the local population was found to mostly consume imported food crops. According to Murphy (19981) and Weil (1986), the rural Kiang West District is inhabited almost entirely by women, since most of the men have migrated to urban areas to earn money in non-agricultural businesses. Although the women living in the CDR area in The Gambia were reported to still cultivate small gardens, the bulk of the diets were bought in markets, where Asian products clearly ruled the market with regard to cheap prices (Murphy, 1981; Weil, 1986). Considering that food consumption in the CDR areas might not be based on locally grown products, one may scrutinize the link between local environmental conditions and CDR disease.

In summary, analyses on the food quality of a CDR area in Bangladesh found locally consumed products to neither be deficient nor to be polluted in any specific element. A progressive use of modern, high-yield crop varieties was identified in most CDR areas, which may have caused a lack of specific micronutrients. However, to what extent the parents of the CDR-affected children depend on locally grown food or depend on foodstuffs that are bought as (imported) products in the market remains unclear. Thus, further analyses on the sources of seeds and food crops in the CDR areas are recommended.

3.8 Synthesis and general discussion

3.8.1 Comparisons between the Kaduna study sites

The villages of the Kaduna study area were classified into three groups: villages where the prevalence rate of Ca-deficiency rickets (CDR) was above average (> 5%) were classified as CDR-high-risk (HR) villages, villages where the CDR prevalence rate was less or equal average (≤ 5%) were classified as CDR-low-risk (LR) villages and villages where CDR was unknown were classified as CDR-no-risk (NR) villages. Among 11 study sites, there were 7 HR villages (Pam Madaki, Ungwan Bagudu, Koche Koche, Kaso, Telele, Ungwan Fada, Jankassa), 3 LR villages (Panzato, Kujama, Kafari) and one NR village (Dakala) (see Chapter 2.2).

Comparisons between the different study sites showed the HR, LR and NR areas to be underlain by Older Granites, a bedrock type which was low in Ca compared to other rock types worldwide. Thin-section analyses furthermore showed that the Older Granites contain considerable contents of biotite minerals (see Chapter 3.1), which are host minerals for F, a PTE which is known to affect bone health in humans when existing in elevated concentrations in the environment (Edmunds & Smedley, 2013; Fantong et al., 2010; Shitumbanuma et al., 2007). However, due to the similarity of the bedrock types between the HR, LR and NR villages, a link between the Older Granite geology, the enrichment of certain trace elements in the local ecosystems and the food crops and the CDR in the local subsistence farmers' children was assumed to be unlikely in the Kaduna study area.

No difference was found with regard to the land use in the HR, LR and NR study sites of the Kaduna study area (see Chapter 3.3). All the study sites were likewise intensively cultivated, while the cash-crop production exceeded the food-crop production. Fertilizers and plant-protection products were used only in small quantities and influxes of PTEs through these sources were assumed to be negligibly low. Thus, an enrichment of agricultural or industrial contaminants was considered unlikely to be a predisposing factor for the CDR in the rural parts of the Kaduna study area.

The soil types, which were analysed only in one HR and one LR village were different between the two study sites (see Chapter 2.2). While in the HR village Kaso, Acrisols and Plinthosols on pisolite slope deposits were the dominant soil forms, in the LR village Panzato the dominant soils forms were Lixisols and Acrisols that have developed on grus slope deposits. The soils in the HR village Kaso were mostly silty, while the soils in the LR village Panzato were sandy. The difference in the texture was assumed to be due to differences in the parent material and erosion rates. Analysis on the mineralogical makeup of the clay fractions showed very high kaolinite contents in the HR-village soils while the LR-village soils also contained considerable contents of illite. The HR-village soils had lower pH values, slightly higher OC concentrations, a higher CECpot but a lower BS than the soils in the LR village. The differences were assumed to be caused by differences in the parent material, clay mineralogy and erosion rates between the two study sites. With regard to the macronutrient concentrations, the HR-village soils contained higher concentrations of plant-available Ca and P and slightly lower K concentrations than the LR-village soils. The plant-available Mg concentrations were similarly low in both the HR-village soils and the LR-village soils. The total Cu and Se concentrations were higher and the total Zn concentrations were lower in the HR-village soils compared to the LR-village soils. Water-soluble Se concentrations were similarly low in both the HR-village soils and the LR-village soils. With regard to the PTEs, the total Cd, Fe, Pb and Sr concentrations were higher in the HR-village soils than in the LR-village soils. Assuming that the CDR in the Kaduna study area is caused by either a deficiency of macronutrients and micronutrients or an oversupply of PTEs in the soil-plant-human pathway, one would expect these deficiencies or oversupplies to be more distinct in the HR-village soils than in the LR-village soils. Although elements were significantly lower or higher in the HR-village soils than in the LR-village soils, comparisons of their concentrations to West African background levels and critical limits showed none of the macronutrients and micronutrients to be critically low and none of the PTEs to be critically elevated. Thus, a deficiency of macronutrients and micronutrients or an oversupply of PTEs in the soils of the Kaduna study area was considered unlikely to have caused CDR in the Kaduna study area.

With regard to the drinking water (see Chapter 3.5), the water in the HR study sites had slightly higher pH values, significantly lower Ca concentrations, slightly higher Se concentrations and lower F concentrations than the water in the LR and NR study sites. However, compared to the WHO guideline levels for drinking water quality (WHO, 2011; 2009), all the elements were within safe ranges. Compared to the typical mineral concentrations of drinking water in areas with Kashin-Beck disease (Fordyce, 2013; Zhang et al., 2011), the Se concentrations of the drinking water in the Kaduna study area were assessed to be marginal, but not critically low. This result is in agreement with the results of the soil analyses, in which the water-soluble Se concentrations were found to be marginal in all the soils of the Kaduna study area. However, as the food and not the drinking water is the primary source of the human Se supply (Fairweather-Tait et al., 2011), the marginal Se concentrations of the drinking water in the Kaduna study area were considered unlikely to have caused CDR in the Kaduna study area. Furthermore, the Se concentrations in both drinking water and soils were marginal, but not critically low, meaning that a link between Se deficiency in the environment and CDR in humans is unlikely.

The maize in the Kaduna study area (see Chapter 3.6) showed no significant differences between the macronutrient or micronutrient contents with regard to study site, but was low in macronutrients and micronutrients compared to West African food composition tables. Especially the modern maize varieties, which were introduced into the Kaduna study area in the 1960s, were marginal in Se and Ca. With regard to the PA contents, the maize in the HR villages contained higher PA contents than the maize in the NR village. Comparisons between the varieties showed the PA contents in the modern maize to be higher than in the traditional maize varieties. A nutritional change from the nutrient-rich and PA-poor traditional maize varieties to the nutrient-poor, PA-rich modern maize varieties was assumed to may have caused changes in the human mineral intake and may thus have a certain impact in the Ca deficiency in the CDR-affected children living in the Kaduna study area. Further analyses on the macronutrient, micronutrient and PA contents in traditional and modern maize are needed to prove this assumption.

In summary, analyses on the bedrock, soils and drinking water in the HR, LR and NR study sites in the Kaduna study area showed no significant differences between the study sites. None of the macronutrients, micronutrients or PTEs analysed in this study was significantly deficient or enriched in the bedrock, soils or drinking water of the Kaduna study area compared to (West African) background levels and international critical limits. Macronutrients and micronutrient contents in the maize were not significantly different between the HR and LR study sites, but were lower in the modern maize varieties than in the traditional maize varieties. In addition, the HR-villages maize contained higher PA contents than the LR-villages maize, while PA contents were always highest in the modern maize varieties. A nutritional change from the nutrient-rich and PA-poor traditional maize varieties to the nutrient-poor and PA-rich modern maize varieties may be a predisposing factor for the CDR in the Kaduna study area. However, further analyses on the varieties and their nutritional quality are needed to prove this assumption.

3.8.2 Comparisons between the CDR areas in Bangladesh, Nigeria, South Africa and The Gambia

Apart from the analysis of bedrock, parent material, land use, soil type, soil physicochemical parameters, drinking water and maize in the CDR area near Kaduna City, northern Nigeria, a literature review was made on the environmental conditions of 7 other CDR areas within other developing countries, including the Chittagong, Jessore and Sylhet districts in Bangladesh, the Kwoi, Kachia and Jos local government areas in Nigeria, the Gert Sibande District in South Africa and the Kiang West District in The Gambia (see Table 2.5).

In the Chittagong District, the Kaduna study area, the Jos Local Government area and the Kiang West District, CDR prevalence rates were 8.7% (Kabir, 1998; Kabir et al., 2004), 5,0% (based on own calculations; see Chapter 2.1), 9.0% (Pfitzner et al., 1998) and less than 0.6% (Jones et al., 2009), respectively. In the Gert Sibande District, approximately 13% of the paediatric population had hypocalcaemia (Pettifor et al., 1981). For the other districts and areas, no prevalence statistics were available (see Chapters 1.1 and 2.6). While CDR is on the increase in Nigeria and Bangladesh, CDR prevalence rates are currently on the decrease in South Africa and The Gambia (Prof. Pettifor, Dr Prentice, Dr Goldberg, personal communication; see Chapter 2.1).

With regard to bedrock and parent materials, all the CDR areas presented in this study showed great variations in age and mineral composition. In Bangladesh, Quaternary, potentially fertile alluvial deposits were the main parent material (FAO, 1988), in The Gambia, Tertiary, mineral-poor sandstone was the dominant bedrock (Jarrett, 1949; Schlüter, 2006) and CDR areas in Nigeria and South Africa were underlain by granitoid and gneissic bedrock of Archean to Jurassic age (Hill, 1978; Wall, 1979). A specific bedrock or parent material age or a specific bedrock or parent material type was therefore considered unlikely to be a predisposing factor for the CDR in developing countries.

As granites are known to often contain higher contents of F-bearing minerals (Edmunds & Smedley, 2013), the idea arose that an oversupply of F might have caused CDR in developing countries (Teotia & Teotia, 2008). In fact, thin-section analyses on the Kaduna study area's granites showed relatively high contents of biotite minerals (see Chapter 3.1), which are known to be host minerals for F (Reimann & Caritat, 1998). However, analyses on the soils and drinking water showed the F concentrations to be too low to have any detrimental effects on human health in the Kaduna study area (see Chapters 3.4.9 and 3.5). Analyses on the drinking water in other CDR areas, such as the Chakaria District in Bangladesh, the Jos Local Government area in Nigeria and the Gert Sibande District in South Africa showed that the F concentrations in the water from these areas is likewise very low (Pettifor et al., 2008). F-bearing bedrock and parent materials were therefore considered unlikely to be a predisposing factor for the CDR in developing countries.

The concentrations of macronutrients, micronutrients and PTEs in bedrock, parent materials and soils can affect the local population only when food crops are produced locally. Research on the typical land use in the different CDR areas within developing countries showed that most CDR areas were located in rural areas where the local population relied on subsistence farming as their main food source (Ali et al., 1997; DARDLA, 2005; Hill, 1978; McGregor & Smith, 1952; Wall, 1979). However, in the Kiang West District in The Gambia, the local population was reported to be mostly females whose livelihood was provided by their husbands and sons working in the urban areas of The Gambia and who bought foodstuffs imported from Asia in the local markets (Murphy, 1981; Weil, 1986). A direct link between CDR and subsistence farming is therefore unlikely for some of the CDR areas within developing countries.

To see if the land use in the CDR areas within developing countries is characterized by agricultural overuse, CDR areas within developing countries were analysed for land use practices. It thereby became apparent that all the CDR areas located in rural areas of developing countries were highly agriculturally-used, while cash-crop production occupied an ever-growing part of the land surfaces (Ali et al., 1997; DARDLA, 2005; Hill, 1978; McGregor & Smith, 1952; Wall, 1979). However, in those CDR areas that were located in urban areas, agricultural use was negligibly low (Combs & Hassan, 2008; Pfitzner et al., 1998). A direct link between CDR and agricultural overuse may therefore be a predisposing factor for the CDR in rural areas, but is, in all probability, not a predisposing factor for CDR in general.

High influxes of PTEs in soils of rural areas are most often linked to agricultural overuse (Bilsborrow, 1992; McMichael, 2000; Plant et al., 1996), while an oversupply of trace elements in urban areas is often due to industrial overuse (Awomeso et al., 2010; Zessa & Tasciotti, 2010). The different CDR areas in developing countries were found in both rural and urban areas (Pettifor et al., 1979). In rural areas, such as the Kaduna study area, fertilizers and plant-protection products were used only in small quantities and influxes of PTEs through these sources were assumed to be negligibly low (see Chapter 3.3). In addition, rural CDR areas were always located far away from industrial complexes and influxes of PTEs were assumed to be negligibly low in these rural CDR areas (Ali et al., 1997; DARDLA, 2005; Hill, 1978; Wall, 1979). Urban CDR areas had a high density of industrial complexes and the concentrations of PTEs were high not only in the soils but also in the CDR cases (Keating et al., 2011; Wright et al., 2005). However, as an enrichment of PTEs in the soils and CDR children was found only in the urban CDR areas but not in the rural CDR areas, an exposure to the toxic effects of industrial environmental contaminants may be a predisposing factor to the CDR in urban areas, but is, in all probability, not predisposing to the CDR in general.

As the capacity of a soil to provide balanced amounts of macronutrients, micronutrients as well as PTEs to plants highly depends on the soil type (Scheffer & Schachtschabel, 2002), analyse on the specific soil types in the different CDR areas within developing countries were of interest. A review on the typical soil-type distribution in the CDR areas of Bangladesh, Nigeria, South Africa and The Gambia showed that the soil types in these areas were different. In the Kaduna study area, for instance, the main soil types were Lixisols, Fluvisols, Acrisols and Plinthosols which contained high contents of low-activity clay minerals, were shallow and susceptible to erosion (see Chapter 3.4.1). In the CDR areas of

South Africa and The Gambia, the main soil types were Lithosols, Regosols and Acrisols which were of potentially low quality (Giglioli & Thornton, 1965; Turner, 2000). In contrast, the soil types typically found in the CDR areas of Bangladesh and Nigeria were Cambisols and Alisols that had developed on macronutrient- and micronutrient-rich parent materials, such as basalts or deltaic deposits (FAO, 1988; Hill, 1978). A clear link between the distribution of specific soil types and the prevalence of CDR was not found. Although soil types with a limited agricultural suitability may predispose to the CDR in some of the African CDR areas, soil types of minor soil quality are, in all probability, not a predisposing factor for the CDR in general.

Laboratory and review data on the physical conditions of the soils in the different CDR areas within developing countries showed that the soils of the CDR areas in Bangladesh, Nigeria, South Africa and The Gambia had most different soil textures, ranging from sandy, to loamy to clayey and providing minor, to medium to very good physical soil conditions with regard to productive soil cultivation (FAO, 1988; Giglioli & Thornton, 1965; Hill, 1978; Rensburg et al., 2009; Turner, 2000; Wall, 1979). A dominance of specifically unfavourable soil particle sizes was not found and a link between specific physical soil conditions and the CDR was considered unlikely.

With regard to clay minerals, the soils in the CDR areas of Bangladesh, Nigeria and South Africa were found to contain considerably high contents of low-activity clay minerals, such as kaolinite (Hill, 1978; Rensburg et al., 2009; Turner, 2000; Wall, 1979). In the CDR areas of Bangladesh, however, the soils were mostly free of kaolinite (FAO, 1988; Huq & Shoaib, 2013). High contents of low-activity clay minerals may therefore be a predisposing factor for the CDR in the African CDR areas, but is, in all probability, not predisposing to the CDR in the Asian CDR areas.

With regard to the macronutrient and micronutrient concentrations of the soils in the different CDR areas within developing countries, the soils of the African CDR areas, including those of the Kaduna study area, the Kwoi, Kachia and Jos local government areas in Nigeria, the Gert Sibande District in South Africa and the Kiang West District in The Gambia, had a moderate to low soil fertility (Giglioli & King, 1966; Marius, 1982; Rensburg et al., 2009; Turner, 2000; Wall, 1979). From the CDR areas around Jos City, northern Nigeria and from the CDR areas in Bangladesh, the distribution of soils with relatively high macronutrient concentrations were reported (FAO, 1988; Hill, 1978; Huq & Shoaib, 2013). Analyses on the soils in the Kaduna study area furthermore showed that the local soils were low but not deficient in macronutrients and micronutrients (see Chapter 3.4.7) and that there were no element interdependencies inhibiting the availability of the macronutrients and micronutrients in the soils (see Chapter 3.4.10). A macronutrient and micronutrient deficiency in the soils was therefore considered unlikely to be a predisposing factor for the CDR in developing countries.

With regard to the concentrations of PTEs in the soils, no significant oversupply was identified in the soils of the Kaduna study area (see Chapter 3.4.9). However, as only the total but not the plant-available concentrations of some PTEs were analysed, the concentrations of PTEs finally reaching the plants and the humans in the Kaduna study area remained unclear. In a CDR area in Jos City, northern Nigeria, the soils and the serum of the local population was elevated in Pb concentrations (Keating et al., 2011; Wright et al., 2005). However, as Pb concentrations in humans were elevated not only in the serum of the CDR cases but were also elevated in the serum of healthy children, the environmental Pb oversupply was assumed to only be an expression of the urban environment. This assumption was also confirmed by findings from Bangladesh, according to which the concentrations of PTEs in serum of rural CDR children are within normal ranges (Cimma et al., 2004). The link between an oversupply of PTEs in soils and the CDR in rural areas was therefore assumed to be unlikely. Further analyses on the soil geochemistry of urban CDR areas are needed to finally evaluate the impact of a soil contamination on the CDR in urban areas.

Apart from the soil quality, also the quality of the drinking water in the different CDR areas within developing countries was of interest in this study. In the Kaduna study area, the drinking water was found to contain sufficient concentrations of macronutrients and micronutrients (see Chapter 3.5) and low concentrations of F compared to the WHO guideline levels (WHO, 2011; 2009). Only the Se concentrations were marginal in the drinking water of the Kaduna study area compared to the mean Se concentrations of the drinking water in areas with Kashin-Beck disease (Zhang et al., 2011). No difference was found between the macronutrient, micronutrient and PTE concentrations of surface and groundwater in the Kaduna study area (see Chapter 3.5). From other CDR areas, the Ca concentrations were found to be sufficient and the F concentrations were reported to be very low. No difference was detected between the macronutrient, micronutrient and PTE concentrations of surface and groundwater (Jordan et al., 2008; Meybeck et al., 1987; Mpenyana-Monyatsi et al., 2012; Pettifor et al., 2008; Preez & Barber, 1965; UNICEF, 2011). A link between a macronutrient and micronutrient deficiency or a PTE oversupply in the drinking water and the CDR areas in developing countries was not found.

Apart from the drinking water quality, also the food composition in CDR areas was of interest in this study. Analyses on the maize in the Kaduna study area showed the macronutrient and micronutrient concentrations to be sufficient compared to West African food composition tables (Stadlmayr et al., 2012), except for Ca and Se concentrations, which were marginal (see Chapter 3.6.1). A significant difference was found between the modern and the traditional maize cultivars, while the modern maize was specifically low in Ca and Se. Analyses on the macronutrient, micronutrient as well as PTE contents of the staple foods in CDR areas of Bangladesh showed local foodstuffs to contain sufficient contents of macronutrients and micronutrients and normal contents of PTEs (Welch et al., 1998). Although low contents of Ca and Se were found in the maize of the Kaduna study area, their impact on the CDR in this region remained unknown. The contents of macronutrients and micronutrients in foodstuffs from CDR areas in Bangladesh were within normal ranges, indicating that a lack of macronutrients and micronutrients in foodstuffs is, in all probability, not a predisposing factor for the CDR in general. Further analyses on the food composition of traditional and modern cereals consumed in CDR areas, such as Sylhet and Jessore in Bangladesh, the Jos, Kwoi and Kachia local government areas in Nigeria, the Gert Sibande District in South Africa and the Kiang West District in The Gambia, are needed to check if a change in the staple crops may have increased the lack of macronutrient and micronutrients in humans.

Analyses on the contents of phytic acids (PA) in food crops were made only in maize cobs from the Kaduna study area (see Chapter 3.6.2). It thereby became apparent that the PA contents were significantly higher in the modern than in the traditional maize cultivars. Elevated PA contents in the modern, high-yield maize cultivars were therefore considered to possibly be a predisposing factor to the CDR in the Kaduna study area. To see if high contents of PA are a predisposing factor for the CDR in general, further analyses the PA contents in the staple crops from other CDR areas within developing countries are needed.

Furthermore, a nutritional change was identified to have taken place in all the CDR areas, shifting from mineral-rich crops, such as sorghum or other traditional cereals, to a diet based on modern, high-yield cereals which were assumed to be deficient in some specific macronutrients and micronutrients and to be enriched in PAs (Combs & Hassan, 2005; Craviari et al., 2008; Pettifor, 2004; Welch et al., 1998). In the Kaduna study area, the use of micronutrient-rich herbs and spices was reported to have been abandoned during the last few decades (see Chapter 3.7.5). Thus, not only a shift from a nutrient-rich nutrition towards a nutrient-poor diet, but also a change from a varied to an increasingly one-sided nutrition may be a predisposing factor for the CDR in developing countries. Further analyses should not only investigate the macronutrient, micronutrient and PA contents of the different food crop varieties, but should also include comparative analyses on the traditional nutrition and the modern nutrition in CDR areas of developing countries.

4 Conclusions and outlook

Aim and approach. This doctoral study was conducted to analyse if environmental conditions are a predisposing factor for calcium-deficiency rickets (CDR), a metabolic bone disease in children that became known some 30 years ago from developing countries. To analyse the link between the environment and the prevalence of CDR, on-site analyses were made in a CDR area near Kaduna City, northern Nigeria. Furthermore, a review was made on the environmental conditions of CDR areas in Bangladesh, Nigeria, South Africa and The Gambia. The significance of this doctoral study lies in being the first to analyse the impact of the environment on the CDR in developing countries.

Main findings. The bedrock of the Kaduna study area were Older Granites, which contained relatively high amounts of nutrient- and F-rich minerals. The actual parent materials of the soil formation in the Kaduna study area were grus slope deposits, pisolite slope deposits and river deposits, which comprised considerable amounts of aeolian deposits. No link was found between the distribution of the bedrock and parent materials and the CDR prevalence rates in the Kaduna study area. The land use in the Kaduna study area was found to be dominated by cash-crop production, while fertilizers and plant-protection products were used only in small amounts. An excessive industrial use was not identified in the Kaduna study sites, indicating that an anthropogenic input of PTEs in the local ecosystems of the Kaduna study area is unlikely. The main soil types in the Kaduna study area were Lixisols, Acrisols, Plinthosols and Fluvisols. These soil types were found to be typical for granite-underlain areas in the northern guinea savanna of West Africa. Furthermore, also the physical soil conditions were representative for the soils of the northern guinea savanna: sandy topsoils, clayey subsoils and relatively high contents of kaolinite clay minerals in the clay fractions. With regard to the geochemical composition, no significant difference was found between the soils of the Kaduna study area and the soils of other granite-underlain areas in West Africa. In comparison to background values from endemic bone disease areas and compared to critical limits, the macronutrient, micronutrient and PTE concentrations in the soils of the Kaduna study area were within safe ranges. Furthermore, also in the drinking water, neither a significant lack of macronutrients and micronutrients, nor a noticeable oversupply of PTEs was found compared to background levels, WHO guideline levels as well as critical limits. The maize contained normal contents only with regard to the macronutrients Mg, K and P, but was low in Ca and Se and slightly elevated in PA compared to West African food composition tables. Comparisons between the mineral contents of traditional and modern maize cultivars showed that the traditional maize cultivars, which have been cultivated extensively in the Kaduna study area until the 1960s, contained significantly higher contents of Ca and noticeable lower concentrations of PA than the modern maize cultivars.

In comparison to the results from the Kaduna study area, a literature review on the environmental conditions of the CDR areas in Bangladesh, Nigeria, South Africa and The Gambia showed that the bedrock and parent materials were either rich or poor in minerals and trace elements. Most of these CDR areas were found to be located in plain areas, where soil types were either rich or poor in soil nutrients. The amounts of macronutrients, micronutrients and PTEs in the drinking water and the food crops of the CDR areas were within safe ranges compared to WHO guideline levels and national food composition tables. In all the CDR areas, including the Kaduna study area, a nutritional change towards a one-sided, micronutrient-poor nutrition was found, which was low in meat and milk products and which was based on the cultivation and consumption of high-yield crop plants.

Conclusions. A direct link between environmental conditions and the CDR in the Kaduna study area was considered unlikely, as neither a statistically significant lack of macronutrients and micronutrients, nor a statistically significant oversupply of PTEs was found in the environment of this area. A lack of Ca and Se as well as elevated contents of PA were found in modern maize varieties compared to traditional maize varieties, which was assumed to be due to differences in variety and not due to environmental conditions. The change in the food crop varieties was assumed to have promoted a lack of Ca and Se in human and thus was assumed to may have had influence on the Ca deficiency in the population of the Kaduna study area.

In the CDR areas of Bangladesh, Nigeria, South Africa and The Gambia, most different environmental conditions were found that were, in some cases, hardly comparable to the environmental conditions of the Kaduna study area. A direct link between environmental conditions and CDR in developing countries was therefore considered unlikely. However, a change in the choice of the crop plant varieties and thus a change in the mineral composition of the nutrition was found in all the CDR areas within developing countries, indicating that it is rather the nutrition than the environmental conditions that control the prevalence of CDR.

Future perspectives. The human and economic costs of CDR are enormous and keep minor populations in a downward trend of poverty. To protect future generations from CDR and to develop an CDR early warning system, further research is necessary to determine the factors that are ultimately responsible in causing the CDR in developing countries. To finally be able to exclude the impact of the environment on Ca deficiency and the resulting CDR, further research on the plant-available concentrations of macronutrients, micronutrients and PTEs in the ecosystems of CDR areas in developing countries is necessary. Furthermore, future research should include the determination of the food crop varieties and should analyse their respective macronutrient, micronutrient and PTE contents. In combination with comparative studies on the traditional nutrition and the modern nutrition, the impact of a nutritional change on the prevalence of the CDR in developing countries should finally be verified. Especially towards the end of the dry season, food resources become scarce. Data collection and assessing the birth months of the CDR children should help to identify if a one-sided nutrition during the dry season is a predisposing factor for the CDR in developing countries. In times of climatic changes and increasing demographic stress, such food scarcities could be especially intense.

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Appendix

A Soil study-site descriptions

Table A.1 Field and laboratory numbers of soils in the HR village Kaso.

Primary parent materials	Soil type	Horizon	Depth (cm)	Field No.	Lab No.
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	0-10	Cat 5-1/1	Gab5-1/1
		Bt*	10-40	Cat 5-1/2	Gab5-1/2
	Haplic Lixisol	Ap	0-10	Cat 5-2/1	Gab5-2/1
		Bt*	10+	Cat 5-2/2	Gab5-2/2
	Gleyic Acrisol (chromic)	Ap	0-10	Cat 5-3/1	Gab5-3/1
		Btg*	10-70+	Cat 5-3/2	Gab5-3/2
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	0-15	Cat 1-3/1	LH11-07
		Bto*	15-45	Cat 1-3/2	LH11-08
		2Bov	45-55	Cat 1-3/3	LH11-09
		3Cv	55+	Cat 1-3/4	LH11-10
	Gleyic Acrisol (siltic)	Ap	0-15	Cat 1-4/1	LH11-11
		Bto*	15-25	Cat 1-4/2	LH11-12
		2Cog	25-60	Cat 1-4/3	LH11-13a
		2Crg	60-80	Cat 1-4/4	LH11-14
	Pisoplinthic Acrisol (chromic)	Ahc	0-10	Cat 2-3/1	Gab2-3/1
		Bto*	10-30	Cat 2-3/2	Gab2-3/2
		2Bw	30-60+	Cat 2-3/3	Gab2-3/3
	Haplic Plinthosol (dystric)	Apc	0-15	Cat 1-2/1	LH11-04
		Bv*	15-30	Cat 1-2/2	LH11-05
		Csmv	30+	Cat 1-2/3	LH11-06
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	0-5	Cat 2-2/1	Gab2-2/1
		Btv*	5-30	Cat 2-2/2	Gab2-2/2
		Bov	30-80	Cat 2-2/3	Gab2-2/3
River deposits (clayey)	Gleyic Fluvisol (dystric, arenic)	Ap	0-25	Cat 5-4/1	Gab5-4/1
		Bg	25-80	Cat 5-4/2	Gab5-4/2
		2Bsg*	80-100+	Cat 5-4/3	Gab5-4/3
	Gleyic Fluvisol (dystric, siltic)	Ap	0-20	Cat 1-5/1	LH11-15
		Bsg*	20-60+	Cat 1-5/2	LH11-16
	Gleyic Fluvisol (dystric, siltic)	Ap	0-15	Cat 2-4/1	LH11-20
		Bog*	15-45	Cat 2-4/2	LH11-21
		Cog	45-90	Cat 2-4/3	LH11-22

(*: diagnostic horizon; HR village: CDR prevalence rate > 5%)

Table A.2 Field and laboratory numbers of soils in the LR village Panzato.

Primary parent materials	Soil type	Horizon	Depth (cm)	Field No.	Lab No.
Grus slope deposits	Haplic Lixisol (chromic)	Ap	0-5	Cat 3-1/1	LH11-24
		Bt*	5-55	Cat 3-1/2	LH11-25
		2Btw	55+	Cat 3-1/3	LH11-26
	Haplic Lixisol (colluvic)	Ap	0-20	Cat 4-1/1	LH11-33
		2Btw*	20-50	Cat 4-1/2	LH11-34
		2Bwo	50+	Cat 4-1/3	LH11-35
	Haplic Acrisol (arenic)	Ap	0-15	Cat 4-2/1	LH11-36
		Bo	15-30	Cat 4-2/2	LH11-37
		Bto*	30-50	Cat 4-2/3	LH11-38
		2Bo	50+	Cat 4-2/4	LH11-39
	Haplic Acrisol	Ap	0-10	Cat 4-3/1	LH11-40
		Bto*	10-45	Cat 4-3/2	LH11-41
		Bwo	45+	Cat 4-3/3	LH11-42
	Haplic Acrisol (arenic)	Ap	0-10	Cat 4-4/1	LH11-43
		Bl	10-30	Cat 4-4/2	LH11-44
		Bt*	30-80	Cat 4-4/3	LH11-45
		2Bt	80+	Cat 4-4/4	LH11-46
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	0-10	Cat 3-2/1	LH11-27
		Bt*	10-25	Cat 3-2/2	LH11-28
		2Bt	25+	Cat 3-2/3	LH11-29
River deposits (sandy)	Gleyic Fluvisol (arenic)	Ap	0-20	Cat 3-4/1	Gab3-4/1
		Bg	20-35	Cat 3-4/2	Gab3-4/2
		2Bsg*	35-80+	Cat 3-4/3	Gab3-4/3
		3Cr*	80-95	Cat 3-4/4	Gab3-4/4

(*: diagnostic horizon; LR village: CDR prevalence rate ≤ 5%)

Table A.3 Study-site characteristics of soils in the HR village Kaso.

Primary parent materials	Secondary parent materials	Slope position	Land use	Soil type	Crops
Grus slope deposits	Aeolian deposits	Upper pediment	Rain-fed arable cultivation, agropastoralism	Epileptic Lixisol (arenic)	Dry rice (cash crop)
		Upper pediment	Rainfed arable cultivation, agropastoralism	Haplic Lixisol	Dry rice (cash crop)
	River, slope and aeolian deposits	Lower pediment	Rainfed arable cultivation, agropastoralism	Gleyic Acrisol (chromic)	Dry rice (cash crop)
Pisolite slope deposits	River, slope and aeolian deposits	Lower plain	Rainfed arable cultivation, agropastoralism	Pisoplinthic Acrisol (chromic)	Cassava (food crop)
		Lower plain	Rainfed arable cultivation, agropastoralism	Gleyic Acrisol (siltic)	Maize (food crop)
		Lower plain	Fallow over 30 years	Pisoplinthic Acrisol (chromic)	none
	Aeolian deposits	Upper plain	Rainfed arable cultivation, agropastoralism	Haplic Plinthosol (dystric)	nd
		Upper plain	Fallow over 30 years	Haplic Plinthosol (hyperdystric, clayic)	none
River deposits (clayey)	Slope and aeolian deposits	River Valley	Rainfed arable cultivation, agropastoralism	Gleyic Fluvisol (dystric, arenic)	Paddy rice (cash crop)
		River Valley	Rainfed arable cultivation, agropastoralism	Gleyic Fluvisol (dystric, siltic)	Paddy rice (cash crop)
		River Valley	Rainfed arable cultivation, agropastoralism	Gleyic Fluvisol (dystric, siltic)	Paddy rice (cash crop)

(nd: not determined; HR village: CDR prevalence rate > 5%)

Table A.4 Study-site characteristics of soils in the LR village Panzato.

Primary parent materials	Secondary parent materials	Slope position	Land use	Soil type	Crops
Grus slope deposits	Aeolian deposits	Upper pediment	Rainfed arable cultivation, agropastoralism	Haplic Lixisol (chromic)	Sweet potato (nd)
		Upper pediment	Rainfed arable cultivation, agropastoralism	Haplic Lixisol (colluvic)	Maize (nd)
	River, slope and aeolian deposits	Lower pediment	Rainfed arable cultivation, agropastoralism	Haplic Acrisol (arenic)	Pepper (nd)
		Lower pediment	Rainfed arable cultivation, agropastoralism	Haplic Acrisol	Modern maize (nd)
		Lower pediment	Rainfed arable cultivation, agropastoralism	Haplic Acrisol (arenic)	Sweet potato (nd)
Pisolite slope deposits	River, slope and aeolian deposits	Lower Plain	Fallow over 20 years	Pisoplinthic Acrisol	none
River deposits (sandy)	Slope and aeolian deposits	River Valley	Rainfed arable cultivation, agropastoralism	Gleyic Fluvisol (arenic)	Paddy rice (cash crop)

(nd: not determined; LR village: CDR prevalence rate ≤ 5%)

Table A.5 Physical properties of soils in the HR village Kaso.

Primary parent materials	Soil type	Horizon	Bulk density	Structure	Coatings	Minerals	
						Abundance	Nature
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	BD2	CR, SG	none	very few	Qtz, Fs, Mca
		Bt*	BD3	SG	faint	very few	Qtz, Fs, Mca
	Haplic Lixisol	Ap	BD2	CR	none	many	Qtz, Fs, Mca
		Bt*	BD3	SB	faint	few	Qtz, Fs, Mca
	Gleyic Acrisol (chromic)	Ap	BD2	CR	none	none	Qtz, Fs, Mca
		Btg*	BD3	SB	distinct	few	Fs, Qtz, Mca
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	BD2	CR, PL	none	few	few
		Bto*	BD3	LU	few	common	few
		2Bov	BD3	MA, SB	none	common	Ps
		3Cv	BD3	MA, SB	none	none	none
	Gleyic Acrisol (siltic)	Ap	BD2	LU	none	none	none
		Bto*	BD3	PL, LU	few	few	Ps
		2Cog	BD3	SB	few	none	none
		2Crg	BD3	AB	few	none	none
	Pisoplinthic Acrisol (chromic)	Ahc	BD3	CR	none	many	Ps
		Bto*	BD3	nd	faint	many	Ps
		2Bw	BD3	MA, SB	none	very few	Ps
	Haplic Plinthosol (dystric)	Apc	nd	CR	none	many	Ps
		Bv*	nd	LU	none	common	Ps
		Csmv	nd	MA, SB	none	none	Ps
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	BD2	CR	none	many	Ps
		Btv*	BD2	CR	faint	common	Ps
		Bov	BD3	MA, SB	none	common	Ps
River deposits (clayey)	Gleyic Fluvisol (dystric, arenic)	Ap	BD3-4	LY	none	few	Qtz, Fs, Mca
		Bg	BD2-3	SB	none	few	Qtz, Fs, Mca
		2Bsg*	BD3	SG	none	none	none
	Gleyic Fluvisol (dystric, siltic)	Ap	BD3	LY	very few	none	none
		Bsg*	BD3	SB	very few	none	none
	Gleyic Fluvisol (dystric, siltic)	Ap	BD3	LY	none	none	none
		Bog*	BD3	AB	none	none	none
		Cog	BD3	SB	none	none	none

(*: diagnostic horizon; BD2: bulk density 1.2-1.4 kg dm^3; BD3: bulk density 1.4-1.6 kg dm^3; BD4: bulk density 1.6-1.8 kg dm^3; AB: angular blocky; CR: crumbly; LU: lumpy; LY: layered; MA: massive; PL: platy; SB: subangular blocky; SG: single grain; Fs: feldspar; Mca: mica; Ps: pisolites; Qtz: quartz; HR village: CDR prevalence rate > 5%)

Table A.6 Physical properties of soils in the LR village Panzato.

Primary parent materials	Soil type	Horizon	Bulk density	Structure	Coatings	Minerals	
						Abundance	Nature
Grus slope deposits	Haplic Lixisol (chromic)	Ap	BD2	LU	none	none	none
		Bt*	BD3	MA, SB	abundant	few	Qtz, Fs, Mca
		2Btw	BD3	MA, SB	common	few	Qtz, Fs, Mca
	Haplic Lixisol (colluvic)	Ap	BD2	CR	none	few	Qtz, Fs, Mca
		2Btw*	BD3	MA, SB	common	few	Qtz, Fs, Mca
		2Bwo	BD4	MA, SB	none	many	Qtz, Fs, Mca
	Haplic Acrisol (arenic)	Ap	BD2	CR	none	none	none
		Bo	BD3	MA, AB	none	few	Qtz
		Bto*	BD3	MA, SB	abundant	few	Qtz
		2Bo	BD4	MA, SB	none	many	Qtz, Fs, Mca
	Haplic Acrisol	Ap	BD2	LU	none	few	Qtz
		Bto*	BD3	MA, SB	few	few	Qtz
		Bwo	BD2-3	MA, SB	none	few	Qtz
	Haplic Acrisol (arenic)	Ap	BD2	CR	none	none	none
		Bl	BD3	nd	none	none	none
		Bt*	BD3	LU	few	none	none
		2Bt	BD3	MA, SB	few	few	Qtz
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	BD2	CR	none	none	none
		Bt*	BD3	MA, SB, PL	few	few	Ps
		2Bt	BD3	MA, SB, PL	few	many	Ps
River deposits (sandy)	Gleyic Fluvisol (arenic)	Ap	BD2	SG	none	few	Qtz, Fs
		Bg	BD2	AB	none	few	Qtz, Fs
		2Bsg*	BD2	AB, SG	none	few	Qtz, Fs
		3Cr*	BD2	AB, SG	none	few	Qtz, Fs

(*: diagnostic horizon; BD2: bulk density 1.2-1.4 kg dm^3; BD3: bulk density 1.4-1.6 kg dm^3; BD4: bulk density 1.6-1.8 kg dm^3; AB: Angular blocky; CR: crumbly; LU: lumpy; LY: layered; MA: massive; PL: platy; SB: subangular blocky; SG: single grain; Fs: feldspar; Mca: mica; Ps: pisolites; Qtz: quartz; LR village: CDR prevalence rate ≤ 5%)

Table A.7 Biological properties of soils in the HR village Kaso.

Primary parent materials	Soil type	Horizon	Colour (Munsell)	Mottles	Roots per 100 cm^2	Biological activity
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	7.5YR 4/2	none	few	few
		Bt*	7.5YR 4/5	none	very few	few
	Haplic Lixisol	Ap	7.5YR 4/3	none	few	few
		Bt*	7.5YR 4/4	few, fine	very few	few
	Gleyic Acrisol (chromic)	Ap	7.5YR 4/3	none	few	few
		Btg*	5YR 4/5	few, medium, faint	Very few	few
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	10YR 6/4	nd	few	common
		Bto*	7.5YR 6/6	nd	few	common
		2Bov	7.5YR 6/6	nd	none	none
		3Cv	5YR6/8	nd	none	none
	Gleyic Acrisol (siltic)	Ap	10YR 6/2	none	few	common
		Bto*	10YR 6/3	none	many	common
		2Cog	10YR 7/4	few, fine, faint	many	common
		2Crg	10YR 7/4-10YR 6/2	many, medium, faint	many	common
	Pisoplinthic Acrisol (chromic)	Ahc	7.5YR 5/3	none	few	few
		Bto*	7.5YR 6/6	nd	few	few
		2Bw	7.5YR 6/6	none	very few	few
	Haplic Plinthosol (dystric)	Apc	10YR 5/3	none	Very few	nd
		Bv*	10YR 5/8	none	Very few	nd
		Csmv	2.5YR 5/8	none	none	nd
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	7.5YR 6/6	none	few	few
		Btv*	7.5YR 6/6	none	few	few
		Bov	2.5YR 4/8	none	few	few
River deposits (clayey)	Gleyic Fluvisol (dystric, arenic)	Ap	10YR 5/4	few, fine, faint	few	few
		Bg	10YR 5/5	few, fine, faint	very few	few
		2Bsg*	10YR 6/3-10YR 4/6	many, coarse, prominent	very few	few
	Gleyic Fluvisol (dystric, siltic)	Ap	10YR 4/2	many, fine	very few	none
		Bsg*	10YR 6/2-10YR 4/6	abundant, coarse, prominent	few	none
	Gleyic Fluvisol (dystric, siltic)	Ap	10YR 5/2-10YR 4/6	few, fine, faint	very few	many
		Bog*	10YR 4/3-10YR 4/6	many, fine, faint	very few	few
		Cog	10YR 4/3-10YR 4/6	abundant, fine, faint	very few	none

(*: diagnostic horizon; nd: not determined; HR village: CDR prevalence rate > 5%)

Table A.8 Biological properties of soils in the LR village Panzato.

Primary parent materials	Soil type	Horizon	Colour (Munsell)	Mottles	Roots per 100 cm^2	Biological activity
Grus slope deposits	Haplic Lixisol (chromic)	Ap	10YR 6/4	none	few	common
		Bt*	7.5YR 6/6	many, fine, faint	few	common
		2Btw	7.5YR 6/6	nd	few	common
	Haplic Lixisol (colluvic)	Ap	10YR 5/2	none	few	few
		2Btw*	5YR 4/6	few, fine, faint	very few	common
		2Bwo	5YR 3/4	few, fine, faint	very few	very few
	Haplic Acrisol (arenic)	Ap	10YR 6/4	none	very few	common
		Bo	7.5YR 5/6-5YR 5/8	few, fine, faint	very few	few
		Bto*	7.5YR 5/6-5YR 4/6	few, fine, faint	very few	very few
		2Bo	7.5YR 5/8-5YR 4/6	few, fine, distinct	very few	very few
	Haplic Acrisol	Ap	10YR 6/3	none	very few	many
		Bto*	7.5YR 6/6	very few, fine, faint	very few	many
		Bwo	10YR 6/3-5YR 4/6	very few, fine, distinct	very few	few
	Haplic Acrisol (arenic)	Ap	10YR 5/2	none	very few	few
		Bl	10YR 6/4	none	very few	few
		Bt*	7.5YR 6/6	very few, fine, faint	very few	few
		2Bt	7.5YR 5/6	few, medium, faint	very few	few
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	10YR 5/4	none	few	common
		Bt*	7.5YR 6/4	none	few	common
		2Bt	7.5YR 5/8	few, fine, faint	few	common
River deposits (sandy)	Gleyic Fluvisol (arenic)	Ap	10YR 5/2	very few, fine, distinct	few	few
		Bg	10YR 4/2	few, faint, distinct	few	none
		2Bsg*	10YR 4/2-7.5YR 6/8	abundant, many, prominent	very few	none
		3Cr*	10YR 5/2	few, coarse, distinct	very few	none

(*: diagnostic horizon; nd: not determined; LR village: CDR prevalence rate ≤ 5%)

B Soil laboratory results

Table B.1 Particle-size distribution and depth of soils in the HR village Kaso.

Dominant parent material	Soil type	Horizon	Depth	Sand	Silt	Clay
			(cm)	(%)		
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	0-10	66	26	8
		Bt*	10-40	46	28	26
	Haplic Lixisol	Ap	0-10	62	25	13
		Bt*	10+	51	22	27
	Gleyic Acrisol (chromic)	Ap	0-10	63	20	17
		Btg*	10-70+	28	25	47
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	0-15	31	46	23
		Bto*	15-45	20	37	43
		2Bov	45-55	18	40	42
		3Cv	55+	21	40	39
	Gleyic Acrisol (siltic)	Ap	0-15	19	62	19
		Bto*	15-25	20	62	18
		2Cog	25-60	16	46	38
		2Crg	60-80	17	40	43
	Pisoplinthic Acrisol (chromic)	Ahc	0-10	29	42	29
		Bto*	10-30	28	38	34
		2Bw	30-60+	22	32	46
	Haplic Plinthosol (dystric)	Apc	0-15	43	24	33
		Bv*	15-30	43	35	22
		Csmv	30+	25	31	34
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	0-5	21	37	42
		Btv*	5-30	18	31	51
		Bov	30-80	21	31	48
River deposits (clayey)	Gleyic Fluvisol (dystric, arenic)	Ap	0-25	9	34	57
		Bg	25-80	31	38	31
		2Bsg*	80-100+	53	25	22
	Gleyic Fluvisol (dystric, siltic)	Ap	0-20	13	62	25
		Bsg*	20-60+	15	62	23
	Gleyic Fluvisol (dystric, siltic)	Ap	0-15	25	44	31
		Bog*	15-45	13	63	24
		Cog	45-90	12	57	31

(*: diagnostic horizon; Sand: 2000-63 µm; Silt: 63-2 µm; Clay: < 2 µm; HR village: CDR prevalence rate > 5%)

Table B.2 Particle-size distribution and depth of soils in the LR village Panzato.

Dominant parent material	Soil type	Horizon	Depth	Sand	Silt	Clay
			(cm)	(%)		
Grus slope deposits	Haplic Lixisol (chromic)	Ap	0-5	55	31	14
		Bt*	5-55	37	22	41
		2Btw	55+	31	30	39
	Haplic Lixisol (colluvic)	Ap	0-20	65	24	11
		2Btw*	20-50	39	23	38
		2Bwo	50+	45	20	35
	Haplic Acrisol (arenic)	Ap	0-15	61	30	9
		Bo	15-30	56	25	19
		Bto*	30-50	41	27	32
		2Bo	50+	37	32	31
	Haplic Acrisol	Ap	0-10	27	46	27
		Bto*	10-45	16	39	45
		Bwo	45+	16	40	44
	Haplic Acrisol (arenic)	Ap	0-10	58	36	6
		Bl	10-30	61	33	6
		Bt*	30-80	44	27	29
		2Bt	80+	41	28	31
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	0-10	71	23	6
		Bt*	10-25	61	22	17
		2Bt	25+	40	23	17
River deposits (sandy)	Gleyic Fluvisol (arenic)	Ap	0-20	58	29	13
		Bg	20-35	52	33	15
		2Bsg*	35-80+	60	20	20
		3Cr*	80-95	77	14	9

(*: diagnostic horizon; Sand: 2000-63 µm; Silt: 63-2 µm; Clay: < 2 µm; LR village: CDR prevalence rate ≤ 5%)

Table B.3 Mineralogy of clay fractions of soils in the HR village Kaso.

Dominant parent material	Soil type	Horizon	Kln	Gt	Ill	Qtz	K-Fs	Gbs	Ab
			(%)						
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	nd	nd	nd	nd	nd	nd	nd
		Bt*	nd	nd	nd	nd	nd	nd	nd
	Haplic Lixisol	Ap	nd	nd	nd	nd	nd	nd	nd
		Bt*	nd	nd	nd	nd	nd	nd	nd
	Gleyic Acrisol (chromic)	Ap	nd	nd	nd	nd	nd	nd	nd
		Btg*	nd	nd	nd	nd	nd	nd	nd
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	81.0	16.9	trace	trace	trace	-	trace
		Bto*	68.3	18.9	trace	5.3	trace	-	-
		2Bov	61.3	27.3	trace	5.6	trace	-	-
		3Cv	66.3	18.8	trace	11.1	trace	-	-
	Gleyic Acrisol (siltic)	Ap	73.7	13.7	trace	7.4	trace	-	-
		Bto*	64.7	15.3	trace	15.3	trace	-	-
		2Cog	74.0	11.6	trace	7.2	trace	-	-
		2Crg	71.6	11.3	trace	9.6	trace	-	-
	Pisoplinthic Acrisol (chromic)	Ahc	nd	nd	nd	nd	nd	nd	nd
		Bto*	nd	nd	nd	nd	nd	nd	nd
		2Bw	nd	nd	nd	nd	nd	nd	nd
	Haplic Plinthosol (dystric)	Apc	68.5	19.1	trace	trace	trace	trace	trace
		Bv*	63.0	37.0	trace	trace	trace	trace	trace
		Csmv	72.8	21.7	trace	trace	trace	trace	trace
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	nd	nd	nd	nd	nd	nd	nd
		Btv*	nd	nd	nd	nd	nd	nd	nd
		Bov	nd	nd	nd	nd	nd	nd	nd
River deposits	Gleyic Fluvisol (dystric, arenic)	Ap	nd	nd	nd	nd	nd	nd	nd
		Bg	nd	nd	nd	nd	nd	nd	nd
		2Bsg*	nd	nd	nd	nd	nd	nd	nd
	Gleyic Fluvisol (dystric, siltic)	Ap	65.4	11.4	trace	15.6	trace	-	-
		Bsg*	79.0	14.5	-	5.5	-	trace	-
	Gleyic Fluvisol (dystric, siltic)	Ap	32.8	63.4	trace	trace	trace	-	-
		Bog*	69.5	13.3	trace	11.2	trace	-	-
		Cog	62.5	26.6	trace	10.9	trace	-	-

(*: diagnostic horizon; nd: not determined; Ab: albite; Fs: feldspar; Gbs: gibbsite; Gt: goethite; Ill: illite; Kln: kaolinite; Qtz: quartz; -: not traceable; trace: < 5%; HR village: CDR prevalence rate > 5%)

Table B.4 Mineralogy of clay fractions of soils in the LR village Panzato.

Dominant parent material	Soil type	Horizon	Kln	Gt	Ill	Qtz	K-Fs	Gbs	Ab
			(%)						
Grus slope deposits	Haplic Lixisol (chromic)	Ap	58.1	20.4	11.8	-	9.7	-	-
		Bt*	64.4	21.3	14.3	-	trace	-	-
		2Btw	67.8	13.8	15.6	-	trace	-	-
	Haplic Lixisol (colluvic)	Ap	50.2	17.6	14.8	14.6	-	trace	-
		2Btw*	71.3	11.3	15.3	trace	-	trace	-
		2Bwo	69.4	11.9	11.6	6.4	-	trace	-
	Haplic Acrisol (arenic)	Ap	50.5	35.6	trace	10.5	trace	-	-
		Bo	73.4	16.0	10.6	trace	trace	-	-
		Bto*	68.3	22.0	9.7	trace	trace	-	-
		2Bo	66.3	19.3	10.1	trace	trace	-	-
	Haplic Acrisol	Ap	61.4	25.9	trace	8.4	trace	-	-
		Bto*	70.6	14.5	10.3	trace	trace	-	-
		Bwo	64.2	20.5	8.7	trace	trace	-	-
	Haplic Acrisol (arenic)	Ap	52.1	27.3	5.5	9.4	5.7	-	-
		Bl	52.9	17.3	8.7	13.6	7.5	-	-
		Bt*	59.6	16.9	10.1	7.6	5.9	-	-
		2Bt	67.8	18.3	8.9	4.9	trace	-	-
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	41.5	31.9	12.3	9.9	3.9	trace	-
		Bt*	51.8	19.8	16.3	12.1	-	-	-
		2Bt	63.5	14.3	14.7	3.3	3.5	trace	-
River deposits (sandy)	Gleyic Fluvisol (arenic)	Ap	nd	nd	nd	nd	nd	nd	nd
		Bg	nd	nd	nd	nd	nd	nd	nd
		2Bsg*	nd	nd	nd	nd	nd	nd	nd
		3Cr*	nd	nd	nd	nd	nd	nd	nd

(*: diagnostic horizon; nd: not determined; Ab: albite; Fs: feldspar; Gbs: gibbsite; Gt: goethite; Ill: illite; Kln: kaolinite; Qtz: quartz; -: not traceable; trace: < 5%; LR village: CDR prevalence rate ≤ 5%)

Table B.5 pH values and OC concentrations of soils in the HR village Kaso.

Dominant parent material	Soil type	Horizon	pH	OC
				(%)
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	4.6	0.7
		Bt*	5.6	1.0
	Haplic Lixisol	Ap	5.6	0.7
		Bt*	5.2	0.7
	Gleyic Acrisol (chromic)	Ap	5.8	0.3
		Btg*	4.7	0.2
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	4.7	1.1
		Bto*	4.3	0.4
		2Bov	4.2	0.3
		3Cv	4.3	0.3
	Gleyic Acrisol (siltic)	Ap	4.2	0.8
		Bto*	4.3	0.7
		2Cog	3.9	0.4
		2Crg	3.9	0.4
	Pisoplinthic Acrisol (chromic)	Ahc	5.0	1.2
		Bto*	4.2	0.5
		2Bw	4.0	0.4
	Haplic Plinthosol (dystric)	Apc	4.7	1.2
		Bv*	4.2	0.8
		Csmv	4.9	0.4
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	4.2	1.3
		Btv*	4.0	0.4
		Bov	4.0	0.4
River deposits	Gleyic Fluvisol (dystric, arenic)	Ap	4.1	2.4
		Bg	4.7	0.5
		2Bsg*	5.0	0.4
	Gleyic Fluvisol (dystric, siltic)	Ap	4.0	1.0
		Bsg*	4.2	0.4
	Gleyic Fluvisol (dystric, siltic)	Ap	5.1	0.4
		Bog*	4.6	0.7
		Cog	4.5	1.4

(*: diagnostic horizon; HR village: CDR prevalence rate > 5%)

Table B.6 pH values and OC concentrations of soils in the LR village Panzato.

Dominant parent material	Soil type	Horizon	pH	OC (%)
Grus slope deposits	Haplic Lixisol (chromic)	Ap	6.0	0.8
		Bt*	4.9	0.2
		2Btw	4.8	0.1
	Haplic Lixisol (colluvic)	Ap	5.3	1.0
		2Btw*	4.8	0.5
		2Bwo	4.7	0.2
	Haplic Acrisol (arenic)	Ap	5.7	1.0
		Bo	4.4	0.4
		Bto*	4.2	0.5
		2Bo	4.7	0.1
	Haplic Acrisol	Ap	5.9	1.2
		Bto*	4.1	0.6
		Bwo	4.7	0.4
	Haplic Acrisol (arenic)	Ap	5.6	0.7
		Bl	5.4	0.3
		Bt*	4.9	0.3
		2Bt	4.7	0.1
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	5.5	0.8
		Bt*	4.2	0.5
		2Bt	4.1	0.3
River deposits (sandy)	Gleyic Fluvisol (arenic)	Ap	4.0	0.6
		Bg	4.3	0.3
		2Bsg*	4.8	0.2
		3Cr*	5.7	0.1

(*: diagnostic horizon; LR village: CDR prevalence rate ≤ 5%)

Table B.7 Total and plant-available macronutrient concentrations as well as CECpot and BS of soils in the HR village Kaso.

Dominant parent material	Soil type	Horizon	Total	Plant-available						
			Ca	Ca	K	Mg	Na	CEC pot	BS	P
			(mg kg^{-1})	(cmol kg^{-1})					(%)	(mg kg^{-1})
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	934.0	4.7	0.1	0.6	0.0	9.4	57.4	8.0
		Bt*	411.0	3.7	0.1	0.8	0.0	12.4	37.7	1.0
	Haplic Lixisol	Ap	899.3	4.7	0.3	0.8	0.0	9.8	59.1	8.0
		Bt*	599.0	5.6	0.1	1.2	0.0	12.5	56.0	4.0
	Gleyic Acrisol (chromic)	Ap	610.0	5.0	0.4	0.7	0.0	12.5	56.0	2.0
		Btg*	289.0	5.0	0.3	1.1	0.0	9.9	62.0	1.0
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	422.1	2.9	0.1	0.7	0.0	9.8	38.5	2.0
		Bto*	299.6	2.7	0.1	0.7	0.0	11.0	32.1	1.0
		2Bov	174.4	1.6	0.1	0.4	0.0	9.6	21.8	1.0
		3Cv	149.5	1.3	0.1	0.4	0.0	9.3	19.3	2.9
	Gleyic Acrisol (siltic)	Ap	322.3	1.9	0.0	0.6	0.0	9.6	26.9	4.0
		Bto*	299.3	1.8	0.0	0.7	0.0	8.0	31.6	3.0
		2Cog	223.8	2.1	0.1	0.8	0.0	10.5	28.9	2.0
		2Crg	124.5	1.8	0.1	0.6	0.0	9.5	15.0	2.0
	Pisoplinthic Acrisol (chromic)	Ahc	434.7	3.7	0.1	0.9	0.0	12.5	38.0	1.0
		Bto*	137.1	2.5	0.0	0.4	0.0	9.7	30.5	0.0
		2Bw	99.0	1.9	0.0	0.4	0.0	10.3	22.7	0.0
	Haplic Plinthosol (dystric)	Apc	597.0	2.4	0.1	0.6	0.0	9.1	34.1	3.0
		Bv*	297.4	1.3	0.0	0.2	0.0	8.5	17.9	1.0
		Csmv	99.7	1.4	0.1	1.1	0.1	7.8	33.2	1.0
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	236.8	2.5	0.2	0.7	0.2	13.5	26.2	1.0
		Btv*	62.3	0.9	0.0	0.1	0.0	12.0	6.3	5.0
		Bov	37.4	0.4	0.2	0.0	0.0	12.1	5.2	0.0
River deposits (clayey)	Gleyic Fluvisol (dystric, arenic)	Ap	720.0	6.5	0.1	0.8	0.0	19.5	25.4	4.0
		Bg	435.0	5.0	0.1	0.8	0.0	12.4	47.5	2.0
		2Bsg*	410.0	3.7	0.1	0.6	0.0	9.4	47.1	2.0
	Gleyic Fluvisol (dystric, siltic)	Ap	273.4	0.9	0.0	0.4	0.0	8.8	19.3	2.0
		Bsg*	223.8	1.7	0.1	0.4	0.0	11.1	26.6	2.0
	Gleyic Fluvisol (dystric, siltic)	Ap	322.6	2.3	0.1	1.0	0.0	8.4	40.5	1.0
		Bog*	324.2	2.2	0.0	0.7	0.0	8.5	35.5	2.0
		Cog	473.8	2.3	0.1	1.1	0.1	14.6	28.0	2.0

(*: diagnostic horizon; HR village: CDR prevalence rate > 5%)

Table B.8 Total and plant-available macronutrient concentrations as well as CECpot and BS of soils in the LR village Panzato.

Dominant parent material	Soil type	Horizon	Total	Plant-available						
			Ca	Ca	K	Mg	Na	CEC pot	BS	P
			(mg kg^{-1})	(cmol kg^{-1})					(%)	(mg kg^{-1})
Grus slope deposits	Haplic Lixisol (chromic)	Ap	348.8	2.8	0.3	0.9	0.2	6.7	62.9	3.0
		Bt*	572.7	3.7	0.2	1.6	0.0	11.1	50.4	0.0
		2Btw	371.6	2.7	0.3	0.8	0.2	8.0	50.3	0.0
	Haplic Lixisol (colluvic)	Ap	898.3	3.1	0.2	0.5	0.1	6.4	60.7	2.0
		2Btw*	448.0	5.3	0.1	1.4	0.0	11.9	57.9	0.0
		2Bwo	546.1	3.7	0.4	1.0	0.0	10.1	50.7	0.0
	Haplic Acrisol (arenic)	Ap	521.7	1.3	0.1	0.2	0.0	5.3	62.3	2.0
		Bo	223.4	1.7	0.1	0.4	0.0	4.1	38.6	1.0
		Bto*	224.3	1.4	0.1	0.6	0.0	8.2	26.6	1.0
		2Bo	148.8	4.0	0.1	1.6	0.0	7.9	27.2	0.0
	Haplic Acrisol	Ap	595.4	2.8	0.2	0.9	0.2	12.9	61.2	3.0
		Bto*	273.4	3.4	0.4	1.3	0.1	13.2	31.6	1.0
		Bwo	324.3	2.9	0.4	0.3	0.1	12.5	44.3	1.0
	Haplic Acrisol (arenic)	Ap	495.6	1.2	0.2	0.5	0.0	7.4	46.3	1.0
		Bl	224.9	1.9	0.1	1.0	0.1	2.9	65.8	1.0
		Bt*	224.1	2.1	0.4	0.5	0.0	8.3	40.0	0.0
		2Bt	248.8	4.7	0.3	0.6	0.0	8.0	37.3	0.0
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	399.3	2.1	0.2	0.5	0.1	5.5	54.5	4.0
		Bt*	248.4	1.4	0.1	0.2	0.0	6.2	27.7	2.0
		2Bt	373.4	2.5	0.1	0.5	0.0	8.1	38.3	1.0
River deposits (sandy)	Gleyic Fluvisol (arenic)	Ap	211.8	1.5	0.1	0.2	0.1	6.8	26.9	5.0
		Bg	224.7	1.6	0.1	0.3	0.1	5.5	36.0	0.0
		2Bsg*	223.7	2.5	0.1	0.4	0.1	6.1	50.6	1.0
		3Cr*	212.0	1.4	0.0	0.2	0.0	2.2	77.4	0.0

(*: diagnostic horizon; LR village: CDR prevalence rate ≤ 5%)

Table B.9 Total and water-soluble micronutrient concentrations of soils in the HR village Kaso.

Dominant parent material	Soil type	Horizon	Total			Water-soluble
			Cu	Zn	Se	Se
			(mg kg^{-1})			
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	nd	nd	nd	nd
		Bt*	nd	nd	nd	nd
	Haplic Lixisol	Ap	nd	nd	nd	nd
		Bt*	nd	nd	nd	nd
	Gleyic Acrisol (chromic)	Ap	nd	nd	nd	nd
		Btg*	nd	nd	nd	nd
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	10.9	14.9	0.7	0.007
		Bto*	18.5	23.5	1.4	0.005
		2Bov	19.9	24.9	1.7	0.002
		3Cv	24.9	24.4	1.7	0.002
	Gleyic Acrisol (siltic)	Ap	10.4	14.9	0.2	0.004
		Bto*	10.5	14.5	0.3	0.004
		2Cog	16.9	21.9	0.6	0.003
		2Crg	16.0	21.9	0.9	0.001
	Pisoplinthic Acrisol (chromic)	Ahc	nd	nd	nd	nd
		Bto*	nd	nd	nd	nd
		2Bw	nd	nd	nd	nd
	Haplic Plinthosol (dystric)	Apc	9.5	11.9	0.5	0.006
		Bv*	14.9	15.4	0.9	0.008
		Csmv	24.9	14.0	1.6	nd
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	nd	nd	nd	nd
		Btv*	nd	nd	nd	nd
		Bov	nd	nd	nd	nd
River deposits (clayey)	Gleyic Fluvisol (dystric, arenic)	Ap	nd	nd	nd	nd
		Bg	nd	nd	nd	nd
		2Bsg*	nd	nd	nd	nd
	Gleyic Fluvisol (dystric, siltic)	Ap	12.9	22.4	0.2	0.005
		Bsg*	12.9	17.9	0.4	0.004
	Gleyic Fluvisol (dystric, siltic)	Ap	16.9	22.3	0.4	0.003
		Bog*	20.5	22.4	0.3	0.004
		Cog	19.0	29.9	0.4	0.005

(*: diagnostic horizon; nd: not determined; HR village: CDR prevalence rate > 5%)

Table B.10 Total and water-soluble micronutrient concentrations of soils in the LR village Panzato.

Dominant parent material	Soil type	Horizon	Total			Water-soluble
			Cu	Zn	Se	Se
			(mg kg^{-1})			
Grus slope deposits	Haplic Lixisol (chromic)	Ap	5.5	18.4	0.2	0.005
		Bt*	8.9	32.7	0.6	0.002
		2Btw	12.0	29.5	0.8	0.001
	Haplic Lixisol (colluvic)	Ap	21.0	77.4	1.0	0.007
		2Btw*	12.0	32.4	1.1	0.008
		2Bwo	4.0	11.4	0.7	0.001
	Haplic Acrisol (arenic)	Ap	4.0	12.4	0.1	0.004
		Bo	7.0	15.9	0.4	0.005
		Bto*	11.0	25.4	1.5	0.004
		2Bo	13.9	27.8	1.7	0.001
	Haplic Acrisol	Ap	9.4	25.3	0.6	0.007
		Bto*	14.5	35.9	1.2	0.003
		Bwo	15.0	32.9	1.0	0.002
	Haplic Acrisol (arenic)	Ap	4.0	14.9	0.2	0.005
		Bl	3.5	13.5	0.1	0.006
		Bt*	8.9	28.3	0.9	0.003
		2Bt	11.4	35.3	0.8	0.001
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	4.0	18.0	0.1	0.005
		Bt*	6.5	27.8	0.5	0.007
		2Bt	9.5	39.8	1.1	0.002
River deposits (sandy)	Gleyic Fluvisol (arenic)	Ap	nd	nd	nd	nd
		Bg	nd	nd	nd	nd
		2Bsg*	nd	nd	nd	nd
		3Cr*	nd	nd	nd	nd

(*: diagnostic horizon; nd: not determined; LR village: CDR prevalence rate ≤ 5%)

Table B.11 Total Al and Fe concentrations of soils in the HR village Kaso.

Dominant parent material	Soil type	Horizon	Total	
			Al	Fe
			(%)	
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	nd	1.6
		Bt*	nd	2.5
	Haplic Lixisol	Ap	nd	1.8
		Bt*	nd	2.8
	Gleyic Acrisol (chromic)	Ap	nd	1.9
		Btg*	nd	3.7
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	3.2	2.0
		Bto*	6.2	3.1
		2Bov	7.2	3.2
		3Cv	7.5	5.7
	Gleyic Acrisol (siltic)	Ap	3.0	1.4
		Bto*	3.2	1.3
		2Cog	5.5	2.1
		2Crg	5.2	1.9
	Pisoplinthic Acrisol (chromic)	Ahc	nd	2.5
		Bto*	nd	1.8
		2Bw	nd	2.8
	Haplic Plinthosol (dystric)	Apc	2.5	2.6
		Bv*	4.2	4.4
		Csmv	7.5	8.9
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	nd	1.3
		Btv*	nd	1.2
		Bov	nd	1.6
River deposits (clayey)	Gleyic Fluvisol (dystric, arenic)	Ap	nd	3.5
		Bg	nd	2.8
		2Bsg*	nd	2.6
	Gleyic Fluvisol (dystric, siltic)	Ap	3.0	2.2
		Bsg*	3.0	1.9
	Gleyic Fluvisol (dystric, siltic)	Ap	2.7	4.3
		Bog*	3.2	2.6
		Cog	3.0	3.5

(*: diagnostic horizon; nd: not determined; HR village: CDR prevalence rate > 5%)

Table B.12 Total Al and Fe concentrations of soils in the LR village Panzato.

Dominant parent material	Soil type	Horizon	Total	
			Al	Fe
			(%)	
Grus slope deposits	Haplic Lixisol (chromic)	Ap	2.2	5.3
		Bt*	5.7	1.5
		2Btw	4.5	2.9
	Haplic Lixisol (colluvic)	Ap	9.0	4.9
		2Btw*	5.5	3.1
		2Bwo	1.2	0.9
	Haplic Acrisol (arenic)	Ap	1.5	0.9
		Bo	3.2	1.6
		Bto*	4.7	2.4
		2Bo	6.4	4.3
	Haplic Acrisol	Ap	4.2	2.2
		Bto*	7.2	3.5
		Bwo	6.7	3.5
	Haplic Acrisol (arenic)	Ap	1.7	1.0
		Bl	1.7	1.0
		Bt*	5.2	2.5
		2Bt	6.0	3.4
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	1.7	1.3
		Bt*	2.7	2.1
		2Bt	5.2	3.0
River deposits (sandy)	Gleyic Fluvisol (arenic)	Ap	nd	3.7
		Bg	nd	3.8
		2Bsg*	nd	1.3
		3Cr*	nd	1.2

(*: diagnostic horizon; nd: not determined; LR village: CDR prevalence rate ≤ 5%)

Table B.13 Total Cd, Pb, Sr and F as well as water-soluble F concentrations of soils in the HR village Kaso.

[Data of F analyses of first four soils taken from Breitstadt (unpublished, 2012)]

Dominant parent material	Soil type	Horizon	Total				Water-sol.
			Cd	Pb	Sr	F	F
			(mg kg^{-1})				
Grus slope deposits	Epileptic Lixisol (arenic)	Ap	nd	nd	20.0	101.0	3.3
		Bt*	nd	nd	20.0	132.0	5.0
	Haplic Lixisol	Ap	nd	nd	6.0	117.0	3.5
		Bt*	nd	nd	7.0	238.0	9.2
	Gleyic Acrisol (chromic)	Ap	nd	nd	20.0	172.0	6.1
		Btg*	nd	nd	25.0	317.0	17.1
Pisolite slope deposits	Pisoplinthic Acrisol (chromic)	Ap	0.012	13.8	5.0	84.5	7.2
		Bto*	0.002	18.4	10.0	80.5	nd
		2Bov	0.001	18.0	5.0	99.2	7.0
		3Cv	0.001	22.9	5.0	85.8	nd
	Gleyic Acrisol (siltic)	Ap	0.005	16.8	9.9	77.9	nd
		Bto*	0.004	16.6	10.0	94.6	7.1
		2Cog	0.001	21.1	5.0	111.0	nd
		2Crg	0.000	21.9	5.0	138.0	nd
	Pisoplinthic Acrisol (chromic)	Ahc	nd	nd	4.0	nd	nd
		Bto*	nd	nd	2.0	nd	nd
		2Bw	nd	nd	2.0	nd	nd
	Haplic Plinthosol (dystric)	Apc	0.009	11.8	5.0	100.0	5.0
		Bv*	0.005	16.1	5.0	151.0	5.0
		Csmv	0.002	16.1	5.0	94.3	10.7
	Haplic Plinthosol (hyperdystric, clayic)	Ahc	nd	nd	3.0	nd	nd
		Btv*	nd	nd	1.0	nd	nd
		Bov	nd	nd	1.0	nd	nd
River deposits (clayey)	Gleyic Fluvisol (dystric, arenic)	Ap	nd	nd	30.0	286.0	4.9
		Bg	nd	nd	25.0	236.0	5.1
		2Bsg*	nd	nd	20.0	190.0	5.8
	Gleyic Fluvisol (dystric, siltic)	Ap	0.008	21.5	9.9	89.0	5.8
		Bsg*	0.002	18.5	9.9	87.2	5.9
	Gleyic Fluvisol (dystric, siltic)	Ap	0.005	14.4	5.0	nd	nd
		Bog*	0.007	22.2	10.0	nd	nd
		Cog	0.019	20.8	10.0	nd	nd

(*: diagnostic horizon; nd: not determined; HR village: CDR prevalence rate > 5%)

Table B.14 Total Cd, Pb, Sr and F as well as water-soluble F concentrations of soils in the LR village Panzato.

Dominant parent material	Soil type	Horizon	Total				Water-sol.
			Cd	Pb	Sr	F	F
			(mg kg^{-1})				
Grus slope deposits	Haplic Lixisol (chromic)	Ap	0.003	9.3	10.0	144.0	8.0
		Bt*	0.000	16.4	5.0	210.0	nd
		2Btw	0.003	18.4	5.0	288.0	16.9
	Haplic Lixisol (colluvic)	Ap	0.015	9.0	20.0	181.0	nd
		2Btw*	0.004	16.1	10.0	253.0	nd
		2Bwo	nd	nd	9.9	337.0	13.3
	Haplic Acrisol (arenic)	Ap	0.002	8.7	9.9	nd	nd
		Bo	0.003	11.3	5.0	91.3	nd
		Bto*	0.000	15.6	5.0	nd	nd
		2Bo	0.003	24.4	9.9	nd	nd
	Haplic Acrisol	Ap	nd	nd	9.9	nd	nd
		Bto*	nd	nd	9.9	203.0	10.9
		Bwo	nd	nd	10.0	302.0	12.0
	Haplic Acrisol (arenic)	Ap	nd	nd	9.9	57.9	nd
		Bl	nd	nd	5.0	65.0	6.6
		Bt*	nd	nd	5.0	91.5	10.8
		2Bt	nd	nd	5.0	228.0	nd
Pisolite slope deposits	Pisoplinthic Acrisol	Ah	0.005	9.0	10.0	137.0	6.9
		Bt*	0.003	12.4	5.0	233.0	nd
		2Bt	0.003	16.2	10.0	194.0	nd
River deposits (clayey)	Gleyic Fluvisol (arenic)	Ap	nd	nd	1.0	nd	nd
		Bg	nd	nd	2.0	nd	nd
		2Bsg*	nd	nd	3.0	nd	nd
		3Cr*	nd	nd	1.0	nd	nd

(*: diagnostic horizon; nd: not determined; LR village: CDR prevalence rate ≤ 5%)

C Water laboratory results

Table C.1 pH values as well as Ca, F and Se concentrations of drinking water in the Kaduna study area.

[Data where laboratory numbers are starting with P were taken from Hartmann (unpublished, 2009) and Hartmann & Sponholz, 2012)]

Study site	Sample source	Village	Lab No.	pH	Ca	Se	F
					(mg L^{-1})	(µg L^{-1})	(ppm)
HR villages	Groundwater (well)	Ungwan Bagudu	P035.1	5.0	4.0	nd	nd
			SR-F12-1	nd	nd	nd	0.1
		Kaso	P017	4.5	1.0	nd	nd
			P030.1	4.5	1.0	3.05	nd
			P030.2	4.5	1.0	< 0.10	nd
			0609K2	nd	nd	0.06	nd
		Telele	P092.7	4.5	5.0	nd	nd
			2208TE	nd	nd	< 0.10	nd
		Jankassa	P137.1	4.5	1.0	< 0.10	nd
			P137.2	4.5	1.0	< 0.10	nd
		Koche Koche	KK1709	nd	nd	0.58	nd
		Kaso	P010.1	8.5	11.0	nd	nd
			P010.2	8.5	11.0	nd	nd
		Ungwan Fada	P138	5.0	3.0	nd	nd
	Surface water (river)	Pam Madaki	SR-F96-2	5.8	nd	nd	< 0.1
		Ungwan Bagudu	P046.1	4.5	1.0	nd	nd
		Telele	P067.1	5.0	4.0	nd	nd
			SR-F96-1	6.7	nd	nd	< 0.1
		Ungwan Fada	P103.1	4.5	1.0	nd	nd
LR village	Groundwater (well)	Kafari	P157	5.0	6.0	nd	nd
			1508KA	nd	nd	< 0.10	nd
			SR-F12-4	nd	nd	nd	0.4
	Surface water (river)	Kafari	P156.1	5.0	11.0	nd	nd
NR village	Groundwater (well)	Dakala	Dakala1	6.0	8.0	< 0.10	nd
	Surface water (river)	Dakala	Kaduna	7.5	nd	nd	nd

(nd: not determined; HR villages: CDR prevalence rate > 5%; LR village: CDR prevalence rate ≤ 5%; NR village: CDR prevalence rate = 0%)

D Maize laboratory results

Table D.1 Ca, K, Mg, P and Se contents of maize in the Kaduna study area.
[Data where laboratory numbers are beginning with Wue are taken from Hartmann (unpublished, 2009)]

Study site	Maize variety	Village	Lab No.	Ca	K	Mg	P	Se
				(mg kg^{-1})				(mg kg^{-1})
HR villages	Modern, yellow	Kaso	Gie4	74.2	3092.6	1002.0	2592.9	nd
		Jankassa	WueL3	51.9	3474.9	969.5	2288.8	nd
	Modern, white	Kaso	Gie6	71.3	2557.1	944.0	2045.0	nd
		Jankassa	WueL5	66.3	3650.9	1146.4	3118.8	< 0.01
	Traditional, yellow	Jankassa	WueL2	75.6	3929.0	1294.0	3558.3	nd
		Kaso	Gie5	68.4	2748.4	904.2	2097.1	< 0.01
LR village	Traditional, yellow	Panzato	Gie8	115.6	2311.5	1011.0	1725.9	< 0.01
NR village	Modern, white	Dakala	WueL4	63.1	3487.5	978.6	2884.4	< 0.01
	Traditional, white	Dakala	WueL1	55.2	3436.3	906.2	1826.7	nd

(nd: not determined; HR village: CDR prevalence rate > 5%; LR village: CDR prevalence rate ≤ 5%; NR village: CDR prevalence rate = 0%)

Table D.2 PA contents of maize in the Kaduna study area.

[Data where laboratory numbers are beginning with Wue are taken from Hartmann (unpublished, 2009)]

Study site	Maize variety	Village	Lab No	Phytic acids
				(mg kg^{-1})
HR villages	Modern, yellow	Kaso	Gie4	8780
		Jankassa	WueL3	5960
	Modern, white	Kaso	Gie6	7710
		Jankassa	WueL5	7130
	Traditional, yellow	Jankassa	WueL2	10570
		Kaso	Gie5	5240
LR village	Traditional, yellow	Panzato	Gie8	nd
NR village	Modern, white	Dakala	WueL4	9290
	Traditional, white	Dakala	WueL1	5020

(nd: not determined; PA: phytic acid; HR villages: CDR prevalence rate > 5%; LR village: CDR prevalence rate ≤ 5%; NR village: CDR prevalence rate = 0%)

References

Abe, S.S.; Oyediran, G.O.; Masunaga, T.; Yamamoto, S.; Honna, T. & Wakatsuki, T. (2009): Soil development and fertility characteristics of inland valleys in the rain forest zone of Nigeria: mineralogical composition and particle-size distribution.- Pedosphere, 19: 505-514.

Abdulrahaman, A.A. & Kolawole, O.M. (2006): Traditional preparations and uses of maize in Nigeria.- Ethnobotanical Leaflets, 10: 219-227.

Abrahams, P.W. (2002): Soils: their implication to human health.- The Science of the Total Environment, 291: 1-32.

Abrams, S.A. (2002): Nutritional rickets: an old disease returns.- Nutrition Reviews, 60: 111-115.

Acquaye, D.K.; Ankomah, A.B. & Kanato, I. (1972): Estimation of available copper, iron, manganese and zinc in soils using cation-exchange resins.- Journal of the Science of Food and Agriculture, 23: 1035-1044.

Adams, C.L.; Hambidge, M.; Raboy, V.; Dorsch, J.A.; Sian, L.; Westcott, J.L. & Krebs, N.F. (2002): Zinc absorption from a low-phytic acid maize.- American Journal of Clinical Nutrition, 76: 556-559.

Adedayo, A.K. & Sanda, A.Y. (2011): Mystical powers of witchcraft among the Gbagyis.- Ilorin Journal of Religious Studies, 1: 77-92.

Adepetu, J.A.; Asubiojo, O.I.; Iskander, F.Y. & Bauer, T.L. (1988): Elemental composition of Nigerian harmattan dust.- Journal of Radioanalytical and Nuclear Chemistry, 121: 141-147.

Adetunji, M.T.; Martins, O. & Arowolo, T.A. (2001): Seasonal variation in atmospheric deposition of nitrate, sulphate, lead, zinc and copper in south-western Nigeria.- Communications in Soil Sciences and Plant Analysis, 32: 65-73.

Adewuyi, T.O. (2009): Land degradation assessment in the peri-urban area of Kaduna metropolis, Nigeria.- Indonesian Journal of Geography, 41: 37-51.

Adeyemo, O.K.; Adedokun, O.A.; Yusuf, R.K. & Adeleye, E.A. (2008): Seasonal changes in physico-chemical parameters and nutrient load of river sediments in Ibadan City, Nigeria.- Global NEST Journal, 10: 326-336.

Adeyeye, A. & Ajewole, K. (1992): Chemical composition and fatty acid profiles of cereals in Nigeria.- Food Chemistry, 44: 41-44.

Adriano, D.C. (1986): Trace elements in the terrestrial environment.- 1. ed.; 879 pp.; New York.

Agaja, S.B. (2001): Factors affecting angular deformities of the knees in Nigerian children. Ilorin experience.- West African Journal of Medicine, 20: 246-250.

Agbenin, J.O. & Yakubu, S. (2006): Potassium-calcium and potassium-magnesium exchange equilibria in an acid savanna soil from northern Nigeria.- Geoderma, 136: 542-554.

Agbenin, J.O. (2002): Lead in a Nigerian savanna soil under long-term cultivation.- The Science of The Total Environment, 286: 1-14.

Agunwamba, J.C. (1998): Solid waste management in Nigeria: problems and issues.- Environmental Management, 22: 849-856.

Ahn, P.M. (1970): West African soils.- 3. ed.; 332 pp.; Oxford.

Ahonsi, M.O.; Berner, D.K.; Emechebe, A.M. & Lagoke, S.T. (2004): Effects of ALS-inhibitor herbicides, crop sequence and fertilization on natural soil suppressinevess to striga hermonthica.- Agriculture, Ecosystems and Environment, 104: 453-463.

Akaninwor, J.O. & Okechukwu, P.N. (2004): Comparative nutrient and anti-nutrient levels in commercial and formulated weaning mixtures.- Biokemistri, 16: 15-21.

Akeredolu, F. (1989): Atmospheric environment problems in Nigeria. An overview.- Atmospheric Environment, 23: 783-792.

Akpede, G.O.; Omotara, B.A. & Ambe, J.P. (1999): Rickets and deprivation. A Nigerian study.- Perspectives in Public Health, 119: 216-222.

Alabi, A.A. (2011): Geology and environmental impact assessment and benefit of granitic rocks of Minna area, north-western Nigeria.- Ethiopian Journal of Environmental Studies and Management, 4: 39-45.

Alhadji, A.S. (2011): Evaluating genomic deoxyribonucleic acid (gDNA) of parents and offspring towards determining rickets hereditary link in Gonin Gora, Kaso and Jankassa communities in Kaduna State.- 70 pp.; Ahmadu Bello University Zaria, Nigeria [Master thesis].

Ali, M.M.; Saheed, S.M.; Kubota, D.; Masunaga, T. & Wakatsuki, T. (1997): Soil degradation during the period 1967-1995 in Bangladesh.- Soil Science and Plant Nutrition, 43: 863-878.

Alloway, B.J. (2013): Bioavailability of elements in soils.- In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology. Impacts of the natural environment on public health: 352-373; Amsterdam.

Alloway, B.J. (2009): Soil factors associated with zinc deficiency in crops and human.- Environmental Geochemistry and Health, 31: 537-548.

Alloway, B.J. [Ed.] (1995): Heavy metals in soils.- 2. ed.; 368 pp.; New York.

Ameyan, O. (1985): Variability of soils developed on migmatites in a part of the Middle Belt of Nigeria.- Applied Geography, 5: 309-323.

Anake, W.U.; Adie, G.U. & Osibanjo, O. (2009): Heavy metals pollution at municipal solid waste dumpsites in Kano and Kaduna States in Nigeria.- Bulletin of the Chemical Society of Ethiopia, 23: 281-289.

Anikwe, M.A.N. & Nwobodo, K.C.A. (2002): Long term effect of municipal waste disposal on soil properties and productivity of sites used for urban agriculture in Abakaliki, Nigeria.- Bioresource Technology, 83: 241-250.

Annor, A.E.; Olobaniyi, S.B. & Mücke, A. (1997): Silicate facies iron-formation of the Egbe-Isanlu Paleoproterozoic schist belt, south-west Nigeria.- Journal of African Earth Sciences, 24: 39-50.

Anthony, E. (2009): Agricultural credit and economic growth in Nigeria. An empirical analysis.- Business and Economics Journal, 14: 1-7.

Anudu, G.K.; Obrike, S.E.; Onuba, L.N. & Ikpokente, A.E. (2011): Hydrochemical analysis and evaluation of water quality in Angwan Jeba and its environs, Nasarawa State, north-central Nigeria.- Research Journal of Applied Sciences, 6: 128-135.

Arnaud, J.; Pettifor, J.; Cimma, J.P.; Fischer, P.R.; Craviari, T.; Meisner, C. & Haque, S. (2007): Clinical and radiographic improvement of rickets in Bangladeshi children as a result of nutritional advice.- Annals of Tropical Paediatrics, 27: 185-191.

Arnesen, A.K. & Krogstad, T. (1998): Sorption and desorption of fluoride in soil polluted from the aluminium smelter at Ardal in western Norway.- Water, Air & Soil Pollution, 103: 357-361.

Arnesen, A.K. (1997): Availability of fluoride to plants grown in contaminated soils.- Plant and Soil, 191: 13-25.

Arshad, M.A.; & Martin, S. (2002): Identifying critical limits for soil quality indicators in agro-ecosystems.- Agriculture, Ecosystems and Environment, 88: 153-160.

Arthur, J.T.; Welbeck, J.E. & Kuma, B.A. (1994): Nutritional rickets in Ghanaian children.- Ghana Medical Journal, 27-28: 520-528.

Aspray, T.J.; Prentice, A.; Cole, T.J.; Sawo, Y.; Reeve, J. & Francis, R.M. (2009): Low bone mineral content is common but osteoporotic fractures are rare in elderly rural Gambian women.- Journal of Bone and Mineral Research, 11: 1019-1025.

Asubiojo, O.I.; Nkono, N.A.; Ogunsua, A.O.; Oluwole, A.F.; Ward, N.I.; Akanle, O.A. & Spyrou, N.M. (1997): Trace elements in drinking water and groundwater samples in southern Nigeria.- The Science of the Total Environment, 208: 1-8.

Awomeso, J.A.; Taiwo, A.M.; Gbagdebo, A.M. & Armoro, A.O. (2010): Waste disposal and pollution management in urban areas. A workable remedy for the environment in developing countries.- American Journal of Environmental Sciences, 6: 26-32.

Ayatse, J.O.; Eka, O.U. & Ifon, E.T. (1983): Chemical evaluation of the effect of roasting on the nutritive value of maize (Zea mays, Linn.).- Food Chemistry, 12: 135-147.

Ayodele, O. & Agboola, A. (1981): The relationship between Bray's P1, modified $NaHCO_3$, New Mehlich and $NH_4F.HF$ extractants for P in savannah soils of Western Nigeria.- Nutrient Cycling in Agroecosystems, 2: 89-99.

Bakare-Odunola, M.T.; Kalik-Zik, T.; Garba, M.; Odunola, R.A. & Bello-Mustapha, K. (2012): Nutritional assessment of the diets in rickets prevalent communities in Kaduna State of

Nigeria.- International Journal of Medicine and Medical Sciences, 4: 110-114.

Baker, K.M. (1995): Agriculture and environment. A case study from The Gambia, West Africa.- African Affairs, 94: 67-86.

Baker, D.H. & Halpin, K.M. (1991): Manganese and iron interrelationship in the chick.- Poultry Science, 70: 146-152.

Bako, S.P.; Funtua, I.I. & Ijachi, M. (2004): Heavy metal content on some savanna plant species in relation to air pollution.- Water, Air and Soil Pollution, 161: 125-136.

Bationo, A.; Waswa, B.; Kihara, J. & Kimetu, J. [Eds.] (2007): Advances in integrated soil fertility management in sub-Saharan Africa: challenges and opportunities.- 1. ed.; 1094 pp.; Heidelberg.

Beattie, J.H. & Avenell, A. (1992): Trace element nutrition and bone metabolism.- Nutrition Research Reviews, 5: 167-188.

Belachew, T.; Nida, H.; Getaneh, T.; Woldemariam, D. & Getinet, W. (2005): Calcium deficiency and causation of rickets in Ethiopian children.- East African Medical Journal, 82: 153-159.

Bennett J.G. (1980): Aeolian deposition and soil parent materials in northern Nigeria.- Geoderma, 24: 241-255.

Bennett, J.G.; Hutcheon, A.A.; Kerr, W.B.; Mansfield, J.E. & Rackham, L.J. (1977a): Land resources of central Nigeria. Environmental aspects of the Kaduna Plains. Land forms and soils.- 3. vol.; 277 pp.; Surrey.

Bennett, J.G.; Hutcheon, A.A.; Kerr, W.B.; Mansfield, J.E. & Rackham, L.J. (1977b): Land resources of central Nigeria. Environmental aspects of the Kaduna Plains. Land Systems.- 1. vol.; 341 pp.; Surrey.

Bereket, A. (2003): Rickets in developing countries.- In: Hochberg, Z. [Ed.]: Vitamin D and rickets: 220-232; Basel.

Berglund, M.; Åkesson, A.; Bjellerup, P. & Vahter, M. (2000): Metal-bone interactions.- Toxicology Letters, 112-113: 219-225.

Bhimma, R.; Pettifor, J.M.; Coovadia, H.M.; Moodley, M. & Adhikari, M. (1995): Rickets in black children beyond infancy in Natal.- South African Medical Journal, 85: 668-672.

Bilsborrow, R.E. (1992): Population growth, internal migration and environmental degradation in rural areas of developing countries.- European Journal of Population, 8: 125-148.

Blair Rains, A.; Lawton, R.M.; Mansfield, J.E. & Rose Innes, R. (1977): Land resources of central Nigeria. Environmental aspects of the Kaduna Plains. Climate and vegetation.- 2. vol.; 77 pp.; Surrey.

Blatt, H. & Tracy, R.J. (1996): Petrology. Igneous, sedimentary and metamorphic.- 2. ed.; 529 pp.; New York.

Blatt, H.; Middleton, G. & Murray, R. (1972): Origin of sedimentary rocks.- 1. ed.; 634 pp.; New Jersey.

Boudey, M.; Bureau, F.; Placé, C.; Neuville, D.; Drosdowsky, M.; Arhan, P. & Bouglé, D. (1997): Effect of small variations of aluminium intake on calcium metabolism in young rats.- Journal of Gastroenterology and Nutrition, 24: 124-127.

Bouis, H.E. (2002): Plant breeding: a new tool for fighting micronutrient malnutrition.- Journal of Nutrition, 132: 491S-494S.

Brady, N.C & Weil, R.R. (1999): The nature and properties of soils.- 12. ed.; 881 pp.; New Jersey.

Braithwaite, V.; Jarjou, L.; Goldberg, G.; Jones, H.; Pettifor, J. & Prentice, A. (2011): A follow-up study of Gambian children with rickets-like deformities and elevated plasma FGF23: possible aetiological factors.- Bone, 50: 218-225.

Breitstadt, C. (unpublished, 2012): Fluorid in Böden. Untersuchungen an ackerbaulich genutzten Böden der ländlichen Peripherie von Kaduna, Nigeria.- 64 pp.; Johann Wolfgang Goethe-Universität Frankfurt, Germany [Bachelor thesis].

Breuning-Madsen, H.; Lyngsie, G. & Awadzi, T.W. (2012): Sediment and nutrient deposition in Lake Volta in Ghana due to Harmattan dust.- Catena, 92: 99-105.

Broadley, M.R.; Chilimba, A.D.C.; Joy, E.J.M.; Young, S.D.; Black, C.R.; Ander, E.L.; Watts, M.J.; Hurst, R.; Fairweather-Tait, S.J.; White, P.J. & Gibson, R.S. (2012): Dietary requirements for magnesium, but not calcium, are likely to be met in Malawi based on national food supply data.- International Journal for Vitamin and Nutrition Research, 82: 192-199.

Bürkert, A.; Haake, C.; Ruckwied, M. & Marschner, H. (1998): Phosphorus application affects the nutritional quality of millet grain in the Sahel.- Field Crops Research, 57: 223-235.

Bunnell, J.E.; Finkelman, R.B.; Centeno, J.A. & Selinus, O. (2007): Medical geology. A globally emerging discipline.- Geologica Acta, 5: 273-281.

Burhke, E.; Creasy, L.E.; Croke, J.F.; Feret, F.R.; Jenkins, R. & Kanare, H.M. (1998): Specimen preparation in X-ray fluorescence.- In Burhke, E.; Jenkins, R. & Smith, D.K. [Eds.]: A practical guide for preparation of specimen for X-ray fluorescence and X-ray diffraction analysis: 59–122; Oxford.

Burke, K. & Durotoye, B. (1970): The Quaternary in Nigeria. A review.- Bulletin de l'Association Sénégalaise pour l'Étude du Quaternaire de l'Ouest Africain, 27: 70-96.

Bwibo, N.O. & Neumann, C.G. (2003): The need for animal source food by Kenyan children.- The Journal of Nutrition, 133: 3936S-3940S.

Caen-Vachette, M. & Ekwueme, B.N. (1988): Rb/Sr ages of schists in the metasedimentary belts in south-east Lokoja and their implications for the Precambrian evolution of central Nigeria.- Journal of African Earth Sciences, 7: 127-131.

Cai, S.; Lin, Y.; Zhineng, H.; Xianzu, Z.; Zhaolu, Y.; Huidong, X.; Yuanrong, L.; Rongdi, J.I.; Wenhua, Z. & Fangyuan, Z. (1990): Cadmium exposure and health effects among residents in an irrigation area with ore dressing wastewater.- The Science of The Total Environment, 90: 67-73.

Cakmak, I.; Ozkan, H.; Braun, H.J.; Welch, R.M. & Romheld, V. (2000): Zinc and iron concentrations in seeds of wild, primitive and modern wheats.- Food and Nutrition Bulletin, 21: 401-403.

Calvo, M. & Carpenter, T. (2003): The influence of phosphorus on the skeleton.- In: New, S.A. & Bonjour, J.P. [Eds.]: Nutritional aspects of bone health: 229-265; Cambridge.

Ceruti, P.O.; Fey, M. & Pooley, J. (2003): Soil nutrient deficiencies in an area of endemic osteoarthritis (Mseleni joint disease) and dwarfism in Maputoland, South Africa.- In: Skinner, H.C.W. & Berger, A.R. [Eds.]: Geology and health. Closing the gap: 151-154; New York.

Cetin, E.; Odabasi, M. & Seyfioglu, R. (2003): Ambient volatile organic compound (VOC) concentrations around a petrochemical complex and a petroleum refinery.- Science of the Total Environment, 312: 103-112.

Chianu, J.N. & Tsujii, H. (2004): Determinants of farmer's decision to adopt or not adopt inorganic fertilizer in the savannas of northern Nigeria.- Nutrient Cycling in Agroecosystems, 70: 293-301.

Chilimba, A.D.C.; Young, S.D.; Black, C.R.; Rogerson, K.B.; Ander, E.L.; Watts, M.J.; Lammel, J. & Broadley, M.R. (2011): Maize grain and soil surveys reveal suboptimal selenium intake is widespread in Malawi.- Nature Scientific Reports, 72: 1-9.

Chrysanthus, C. (1997): Lead exposure in Africa.- AMBIO, 26: 399-403.

Ciesielksi, H. & Sterckeman, T. (1997): A comparison between three methods for the determination of cation-exchange capacity and exchangeable cations in soils.- Agronomy, 17: 9-16.

Cimma, J.P.; Arnaud, J.; Labarere, J.; Guillard, O.; Nugues, F.; Marrauld, A.; Durand, C.; Farvacque, J.-M.; Bottari, S.P. & Haque, S. (2004): Effect of consumption of food cooked in aluminium or stainless-steel pots on Bangladeshi children with calcium-deficient rickets: an eight month trial.- Journal of Trace Elements in Medicine and Biology, 17: 249-253.

Combs, G.F. (2013): Geological impacts on nutrition.- In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology. Impacts of the natural environment on public health: 179-194; Amsterdam.

Combs, G.F.; Hassan, N.; Dellagana, N.; Staab, D.; Fischer, P.; Hunt, C. & Watts, J. (2008): Apparent efficacy of food-based calcium supplementation on preventing rickets in Bangladesh.- Biological Trace Element Research, 121: 193-204.

Combs, G.F. & Hassan, N. (2005): The Chakaria food system study: household-level, case-control study to identify risk factor for rickets in Bangladesh.- European Journal of Clinical Nutrition, 59: 1291-1301.

Couppis, O.A.; Emmert, W.K.; Kitz, C.; Vant Hoff, W.; Drake, W.M. & Stich, A. (2006): The metabolic basis of a severe rickets-like deformity in Nigerian children.- Endocrine Abstracts, 12: 14.

Craviari, T.; Pettifor, J.M.; Thacher, T.D.; Meisner, C.; Arnaud, J. & Fischer, P.R. (2008): Rickets: an overview and future directions, with special reference to Bangladesh. A summary of the rickets convergence group meeting, Dhaka, 26–27 January 2006.- Journal of Health, Population and Nutrition, 26: 112-121.

Cronin, S.J.; Manoharan, V.; Hedley, M.J. & Loganathan, P. (2000): Fluoride. A review of its fate, bioavailability and risk of fluorosis in grazed-pasture systems in New Zealand.- New

Zealand Journal of Agricultural Research, 43: 295-321.

Daniels, R.B. & Hammer, R.D. (1992): Soil geomorphology.- 1. ed.; 236 pp.; New York.

DARDLA Department of Agriculture, Rural Development and Land Administration of the Mpumalanga Provinces Government (2005): Resources information report: Mpumalanga.- 1. ed.; 13 pp.; Nelspruit.

Darnley, A.G.; Björklund, A.; Bølviken, B.; Gustavsson, N.; Koval, P.; Plant, J.A.; Steenfelt, A.; Tauchid, M. & Xuejing, X. (1995): A global geochemical database for environmental and resource management.- 19. report; 122 pp.; Paris.

Davies, B.E.; Bowman, C.; Davies, T.C. & Selinus, O. (2013): Medical geology. Perspectives and prospects.- In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology. Impacts of the natural environment on public health: 1-14; Amsterdam.

Davies, T.C. & Mundalamo, H.R. (2010): Environmental health impacts of dispersed mineralization in South Africa.- Journal of African Earth Sciences, 58: 652-666.

Davies, B.E. (1996): Deficiencies and toxicities of trace elements and micronutrients in tropical soils. Limitations of knowledge and future research needs.- Environmental Toxicology and Chemistry, 16: 75-83.

Deckers, J. & Steinnes, E. (2004): State of the art on soil-related geomedical issues in the world.- Advances in Agronomy, 84: 1-35.

Delaure, S. (1998): Soil survey of two pilot villages in the NGS benchmark area of Nigeria.- 110 pp.; Katholieke Universiteit Leuven, Belgium [Master thesis].

Delhaize, E. & Ryan, P.R. (1995): Aluminium toxicity and tolerance in plants.- Plant Physiology, 107: 315-321.

Dev, G. & Rattan, R.K. (1998): Nutrient management issues in red and lateritic soils.- In: Sehgal, J.; Blum, W.E. & Gaijbhiye, K.S. [Eds.]: Red & lateritic soils. Volume 1. Managing red and lateritic soils for sustainable agriculture: 321-337; New Delhi.

Dimitri, P. & Bishop, N. (2007): Rickets.- Paediatrics and Child Health, 17: 279-287.

DIN EN 16279 (2012): Animal feeding stuffs. Determination of fluoride content after hydrochloric acid treatment by ion-sensitive electrode method (ISE).- 1. part; 22 pp; Berlin.

DIN EN 13346 (2001): Characterization of sludge. Determination of trace elements and phosphorus. Aqua regia extraction methods.- 4. part; Berlin.

DIN EN 38406 (1999): German standard methods for the examination of water, waste water and sludge. Analyses of 61 elements in water samples by ICP-MS.- 29. part; Berlin.

DIN EN 38405 (1985): German standard methods for the examination of water, waste water and sludge; anions (group D); determination of fluoride.- 7. part; Berlin.

DIN EN 38405 (1994): German standard methods for the examination of water, waste water and sludge. Determination of selenium by atomic absorption spectrometry.- 23. part; Berlin.

DIN EN 19684 (1977a): Methods of soil analyses for water management for agricultural purposes. Determination of the humus content of a soil.- 2. part; Berlin.

DIN EN 19684 (1977b): Methods of soil analyses for water management for agricultural purposes. Determination of exchange capacity of a soil and of amounts of exchangeable cations.- 8. part; Berlin.

Dissanayake, C.B. & Chandrajith, R. (2009): Introduction to medical geology: focus on tropical environments.- 1. ed.; 297 pp.; Berlin.

Dodd, N.F.; Levy, D.W. & Jackson, W.P.U. (1960): Environmental bone disease of hitherto undescribed type.- South African Medical Journal, 34: 601-611.

Drechsel, P.; Gyiele, L; Kunze, D. & Cofie, O. (2001): Population density, soil nutrient depletion and economic growth in sub-Saharan Africa.- Ecological economics, 38: 251-258.

Drees, L.R.; Manu, A. & Wilding, L.P (1992): Characteristics of aeolian dusts in Niger, West Africa.- Geoderma, 59: 213-233.

Dunnigan, M.G.; Henderson, J.B.; Hole, D.J.; Mawer, B. & Berry, J.L. (2005): Meat consumption reduces the risk of nutritional rickets and osteomalacia.- British Journal of Nutrition, 94: 983-991.

Eberle, J.; Schindmayer, S.; Erben, R.G.; Stangassinger, M. & Roth, H.P. (1999): Skeletal effects of zinc deficiency in growing rats.- Journal of Trace Elements in Medicine and Biology, 13: 21-26.

Edema, M.O.; Sanni, L.O. & Sanni, A.I. (2005): Evaluation of maize-soybean flour blends for sour maize bread production in Nigeria.- African Journal of Biotechnology, 4: 911-918.

Edmunds, W.M. & Smedley, P.L. (2013): Fluoride in natural waters.- In: In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology. Impacts of the natural environment on public health: 311-336; Amsterdam.

Edmunds, W.M. & Smedley, P.L. (1996): Groundwater geochemistry and health. A review.- In: Appleton, J.D.; Fuge, R. & McCall, G.J.H. [Eds.]: Environmental geochemistry and health: 91-105; London.

Egbuniwe, I.G.; Fitches, W.R.; Bentley, M. & Snelling, N.J. (1985): Late Pan-African syenite-granite plutons in NW Nigeria.- Journal of African Earth Sciences, 3: 427-435.

Egli, I.; Davidsson, L.; Walczyk, T. & Hurrell, R. (2004): Dephytinization of a complementary food based on wheat and soy increases zinc, but not copper apparent absorption in adults.- Journal of Nutrition, 134: 1077-1080.

Ekanem, E.E.; Bassey, D.E. & Eyong, M. (1995): Nutritional rickets in Calabar, Nigeria.- Annals of Tropical Paediatrics, 15: 303-306.

Elaigwu, S.E.; Ajibola, V.O. & Folaranmi, F.M. (2007): Studies on the impact of municipal waste dumps on surrounding soil and air quality of two cities in northern Nigeria.- Journal of Applied Sciences, 7: 421-425.

Emechebe, M.A.; Ellis-Jones, J.; Schulz, S.; Chikoye, D.; Douthwaite, B.; Kureh, I.; Tarawali, G.; Hussaini, M.A.; Kormawa, P. & Sanni, A. (2004): Farmers' perception of the striga problem and its control in northern Nigeria.- Experimental Agriculture, 40: 215-232.

Emmert, W.K. (2009): Rachitis-ähnliche Symptome bei nigerianischen Kindern aus der Ethnie der Gbagyi in der südwestlichen Region Kadunas: Identifizierung des biochemischen Defekts, Sammeln von epidemiologischen Daten und Beschreibung des klinischen Bildes.- 163 pp.; Julius-Maximilians-Universität Würzburg, Germany [Doctoral thesis].

Ene-Obong, H.N.; Enugu, E.I. & Uwaegbute, A.C. (2001): Determinants of health and nutritional status of rural Nigerian women.- Journal of Health, Population and Nutrition, 19: 320-330.

Ephraim, B.E. (2012): Granitoids of the Older Granite suites in south-eastern Nigeria.- Advances in Applied Science Research, 3: 994-1007.

Esu, I.E. & Ojanuga, A.G. (1985): Morphological, physical and chemical characteristics of Alfisol in the Kaduna area of Nigeria.- Samaru Journal of Agricultural Research, 3: 39-49.

Eswaran, H.; Coninck, de F. & Varghese, T. (1990): Role of plinthite and related forms in soil degradation.- In: Lal, R. & Stewart, B.A. [Eds.]: Advances in soil science: 109-127; New York.

Eyberg, C.J. & Pettifor, J.M. (1986): Dietary calcium intake in rural black South African children. The relationship between calcium intake and calcium nutritional status.- Human Nutrition Clinical Nutrition, 40: 69-74.

Eyde, B. (1983): Determination of acid soluble fluoride in soils by means of an ion-selective electrode.- Fresenius Zeitschrift für Analytische Chemie, 316: 299-301.

Fagbami, A.; Ajayi, S.O. & Ali, E.M. (1985a): Nutrient distribution in the basement complex soils of the tropical, dry rainforest of south-western Nigeria. Macronutrients calcium, magnesium and potassium.- Soil Science, 139: 431-436.

Fagbami, A.; Ajayi, A. & Ali, E.M. (1985b): Nutrient distribution in the basement complex soils of south-western Nigeria. Micronutrients zinc and copper.- Soil Science, 139: 531-537.

Fagbami, A. (1981): Soil formation processes in the sub-humid tropics on basement complex.- Nigerian Journal of Soil Science, 12: 131-146.

Fahey, J.W. (2005): Moringa oleifera. A review of the medical evidence for its nutritional, therapeutic and prophylactic properties. Part 1.- Trees Life Journal, 1: 1-18.

Fairweather-Tait, S.J.; Bao, Y.; Broadley, M.R.; Collings, R.; Ford, D.; Hesketh, J.E. & Hurst, R. (2011): Selenium in human health and disease. A review.- Antioxidants and Redox Signalling, 14: 1337-1383.

Falola, T. & Heaton, M. (2008): A history of Nigeria.- 1. ed.; 368 pp.; New York.

Fantong, W.Y.; Satake, H.; Ayonghe, S.N.; Suh, E.C.; Adelana, S.M.A.; Fantong, E.B.S.; Banseka, H.S.; Gwanfogbe, C.D.; Woincham, L.N.; Uehara, Y. & Zhang, J. (2010): Geochemical provenance and spatial distribution of fluoride in groundwater of Mayo Tsanaga River Basin, Far North Region, Cameroon. Implications for incidence of fluorosis and optimal consumption dose.- Environmental Geochemistry and Health, 32: 147-163.

FAO (1988): Land resources appraisal of

Bangladesh for agricultural development.- 5. report, 1. volume: computerised land resources inventory; 118 pp.; Rome.

Faure, P. & Volkoff, B. (1998): Some factors affecting regional differentiation of the soils of Benin (West Africa).- Catena, 32: 281-306.

FDALR (1990): Soil map of Nigeria, sheet 3 of 8; 1:650000; Lagos.

Ferré, E.; Deleris, J.; Bouchez, J.L.; Lar, A.U. & Peucat, J. (1996): The Pan-African reactivation of Eburnean and Archean provinces in Nigeria: structural and isotopic data.- Journal of the Geological Society, 153: 719-728.

Fiedler, H.J. & Rösler, H.J. (1993): Spurenelemente in der Umwelt. 2. ed.; 385 pp.; München.

Fildes, V.A. (1986): The English disease: infantile rickets and scurvy in pre-industrial England.- In: Cule, J. & Turner, T. [Eds.]. Child care trough the centuries: 121-134; Cardiff.

Finkelman, R.B.; Skinner, H.C.W.; Plumlee, G.S. & Bunnell, J.E. (2001): Medical geology.- Geotimes, 20: 1.

Fischer, P.R.; Thacher, T.D. & Pettifor, J.M. (2008): Pediatric vitamin D and calcium nutrition in developing countries.- Reviews in Endocrine and Metabolic Disorders, 9: 181-192.

Fischer, P.R.; Thacher, T.D.; Pettifor, J.; Jorde, L.; Eccleshall, T. & Feldmann, D. (2000): Vitamin D receptor polymorphisms and nutritional rickets in Nigerian children.- Journal of Bone and Mineral Research, 15: 2206-2210.

Fischer, P.R.; Rahman, A.; Cimma, J.P.; Kyaw-Myint, T.O.; Kabir, A.; Talukder, K.; Hassan, N.; Manaster, B.J.; Staab, D.B.; Duxbury, J.M.; Welch, R.M.; Meisner, C.A.; Haque, S. & Combs, G.F. (1999): Nutritional rickets without vitamin D deficiency in Bangladesh.- Journal of Tropical Pediatrics, 45: 291-293.

Fjelldal, P.G.; Hansen, T. & Albrektsen, S. (2012): Inadequate phosphorus nutrition in juvenile Atlantic salmon has a negative effect on long-term bone health.- Aquaculture, 334-337: 117-123.

Foley, J.A.; DeFries, R.; Asner, G.P.; Barford, C.; Bonan, G.; Carpenter, S.R.; Stuart, F.; Coe, M.T.; Daily, G.C.; Gibbs, H.K.; Helkowski, J.H.; Holloway, T.; Howard, E.A.; Kucharik, C.J.; Monfreda, C.; Patz, J.A.; Prentice, I.C.; Ramankutty, N. & Snyder, P.K. (2005): Global consequences of land use.- Science, 309: 570-574.

Fordyce, F.M. (2013): Selenium deficiency and toxicity in the environment.- In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology. Impacts of the natural environment on public health: 365-416; Amsterdam.

Fordyce, F.M.; Guangdi, Z.; Green, K. & Xinping, L. (2000): Soil, grain and water chemistry in relation to human selenium-responsive diseases in Enshi District, China.- Applied Geochemistry, 15: 117-132.

Fordyce, F.M.; Masara, D. & Appleton, J.D. (1996): Stream sediment, soil and forage chemistry as indicators of cattle mineral status in north-east Zimbabwe.- In: Appleton, J.D.; Fuge, R. & McCall, G.J.H. [Eds.]: Environmental geochemistry and health. With special reference in developing countries: 23-37; London.

Fowles, J.; Weinstein, P. & Tseng, C.H. (2005): Environmental medicine. In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology. Impacts of the natural environment on public health: 541-562; Amsterdam.

Foy, C.D. (1984): Physiological effects of hydrogen, aluminium and manganese toxicities in acid soil.- In: Adams, F. [Ed.]: Soil acidity and liming: 57-97; Madison.

Frayn, K.N. & Akanji, A.O. (2006): Integration of metabolism 3. Macronutrients.- In: Gibney, M.J.; MacDonald, I.A. & Roche, H.M. [Eds.]: Nutrition and Metabolism: 75-95; Oxford.

Frison, E.A.; Smith, I.F.; Johns, T.; Cherfas, J. & Exzaguirre, P.B. (2006): Agricultural biodiversity, nutrition and health. Making a difference to hunger and nutrition in the developing world.- Food and Nutrition Bulletin, 27: 167-179.

Frossard, E.; Bucher, M.; Mächler, F.; Mozafar, A. & Hurrell, R. (2000): Potential for increasing the content and bioavailability of Fe, Zn and Ca in plants for human nutrition.- Journal of the Science of Food and Agriculture, 80: 861-879.

Fuge, R. (2013): Anthropogenic sources.- In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology. Impacts of the natural environment on public health: 59-74; Amsterdam.

Fullmer, C.S. (1991): Intestinal calcium and lead absorption. Effect of dietary lead and calcium.- Environmental Research, 54: 159-169.

Fung, K.F.; Zhang, Z.Q.; Wong, J.W.C. & Wong, M.H. (1999): Fluoride contents in tea and soil from tea plantations and the release of fluoride into tea liquor during infusion.- Environmental Pollution, 104: 197-205.

Gabriel, M (unpublished, 2012): Investigations into soil quality and the occurrence of rickets in Kaduna, Nigeria.- 201 pp.; Leibniz-Universität Hannover, Germany [Master thesis, *Diplomarbeit*].

Garrett, R.G. (2013): Natural distribution and abundance of elements.- In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology: 35-57; Dordrecht.

Giglioli, M.E.C. & King, D.F. (1966): The mangrove swamps of Keneba, lower Gambia river basin, III. Seasonal variations in the chloride and water content of swamp soils, with observations on the water levels and chloride concentration of free soil water under a barren mud flat during the dry season.- Journal of Applied Ecology, 3: 1-19.

Giglioli, M.E.C. & Thornton, I. (1965): The mangrove swamps of Keneba, lower Gambia river basin, I. Descriptive on the climate, the mangrove swamps and the physical composition of their soils.- Journal of Applied Ecology, 2: 81-103.

Gitonga, A. (2009): Rickets woes dull boom in flower farms.- http://www.standardmedia.co.ke/?articleID=114 4014205&story_title=Rickets-woes-dull-bloom-in-flower-farms [2012/10/13].

Gomes, C. & Silva, J. (2001): Beach sand and bentonite of Porto Santo Island. Potentialities for applications in geomedicine.- In: Gomes, C. & Silva, J. [Eds.]: O liberal. Camara de lobos.- 1. ed.; 66 pp.; Madeira.

Govindaraju, K. (1994): Compilation of working values and sample description for 383 geostandards.- Geostandard Newsletters, 18: 1-158.

Graff, M.; Thacher, T.D.; Fischer, P.R.; Stadler, D.; Pam, S.D.; Pettifor, J.M.; Isichei, C.O. & Abrams, S.A. (2004): Calcium absorption in Nigerian children with rickets.- American Society for Clinical Nutrition, 80: 1415-1421.

Graham, R.D.; Welch, R.M.; Saunders, D.A.; Ortiz-Monasterio, I.; Bouis, H.E.; Bonierbale, M.; Haan, de S.; Burgos, G.; Thiele, G.; Liria, R.; Meisner, C.A.; Beebe, S.E.; Potts, M.J.; Kadian, M.; Hobbs, P.R.; Gupta, R.K. & Twomlow, S. (2007): Nutritious subsistence food systems.- Advances in Agronomy, 92: 1-74.

Graham, R.D. & Welch, R.M. (1996): Breeding for staple food crops with high micronutrient density. Working papers on agricultural strategies for micronutrients.- 3. no.; 79 pp.; Washington.

Graham, R.D. (1984): Breeding for nutritional characteristics in cereals.- Advances in Plant Nutrition, 1: 57-102.

Greenfield, H. & Southgate, D.A.T. (2003): Food composition data. Production, management and use.- 2. ed.; 288 pp.; Rome.

Grusak, M. (2002): Enhancing mineral content in plant food products.- Journal of the American College of Nutrition, 21: 178S-183S.

Hag, El A.I, & Karrar, Z.A. (1995): Nutritional vitamin-D-deficiency rickets in Sudanese children.- Annals of Tropical Paediatrics, 15: 69-76.

Hardy, R. & Tucker, M. (1988): X-ray powder diffraction of sediments.- In: Tucker, M. [Ed.]: Techniques in sedimentology: 191-228; Oxford.

Harland, B.F.; Oke, O.L. & Felix-Phipps, R. (1988): Preliminary studies on the phytate content of Nigerian foods.- Journal of Food Composition and Analysis, 1: 202-205.

Hartmann, L. & Sponholz, B. (2012): Spatial distribution of calcium in food, water and soil and its possible influence on rickets disease in northern Nigeria.- Environmental Geochemistry and Health, 34: 503-512.

Hartmann, L. (submitted): Relevance of cadmium and lead on nutritional rickets in northern Nigeria.- Conference proceedings of Jahrestagung der Gesellschaft für Mineralstoffe und Spurenelemente; Leipzig.

Hartmann, L. (unpublished, 2009): Geochemische Untersuchungen zur Rachitisverbreitung in Zentralnigeria.- 139 pp.; Julius-Maximilians-Universität Würzburg, Germany [Master thesis, *Diplomarbeit*].

Heald, W.R. (1965): Calcium and magnesium.- In: Black, C.A. [Ed.]: Methods of soil analysis: 999-1010; Madison.

Heathcote, R.G. & Stockinger, R.G. (1970): Soil fertility under continuous cultivation in northern Nigeria. Responses to fertilisers in the absence of organic manures.- Experimental Agriculture, 6: 345-350.

Heinrich, J. (1995): Bodengeographische und geomorphologische Untersuchungen zur Landschaftsgenese und aktuellen Geomorphodynamik in der Trockensavanne Nordost-Nigerias.- 197 pp.; Johann Wolfgang Goethe-Universität Frankfurt, Germany [Habilitation thesis].

Hem, J. (1992): Study and interpretation of the chemical characteristics of natural water.- Water Supply Paper 2254; 263 pp.; Reston.

Herrmann, L.; Jahn, R. & Stahr, K. (1996): Identification and quantification of dust additions in peri-Saharan soils.- In: Guerzoni, S. & Chester, R. [Eds.]: The impact of desert dust across the Mediterranean: 173-182; Groningen.

Hill, I.D. [Ed.] (1978): Land resources of central Nigeria. Agricultural development possibilities. The Jos Plateau. Executive summary.- 2. vol. (A); 43 pp.; Surrey.

Hoffmann, I.; Gerling, D.; Kyiogwom, B. & Mané-Bielfeldt, A. (2001): Farmer's management strategies to maintain soil fertility in a remote area in north-west Nigeria.- Agriculture, Ecosystems & Environment, 86: 263-275.

Hojer, B.; Gebre-Medhin, M.; Sterky, G.; Zetterstrom, R. & Daniel, K. (1977): Combined Vitamin-D-deficiency rickets and protein-energy malnutrition in Ethiopian infants.- Journal of Tropical Paediatrics, 23: 73-79.

Hortal, M.; Benitez, A.; Contera, M.; Etorena, P.; Montano, A. & Meny, M.A. (1990): A community-based study of acute respiratory tract infection in children in Uruguay.- Reviews of Infectious Diseases, 12: 966-973.

Hough, R.L. (2010): Bioavailability. Exposure, dose and risk assessment.- In: Hooda, P. [Ed.]: Trace elements in soils: 267-292; Chichester.

Hough, R.L. (2007): Soil and human health. An epidemiological review.- European Journal of Soil Sciences, 58: 1200-1212.

Huq, S.M.I. & Shoaib, J.U.M. (2013): The soils of Bangladesh.- 1. ed.; 165 pp.; Dordrecht.

HVCF (unpublished, 2013): Report of preliminary assessment of rickets cases in Jaba Kingdom in Kaduna State; Kaduna.

HVCF (unpublished, 2011): The number of rickets cases in villages east of Kaduna City in the year 2011; Kaduna.

HVCF (2010): The HVCF Centre.- 1. ed.; 8 pp; Kaduna.

HVCF (unpublished, 2008): The number of rickets cases in villages east of Kaduna City in the year 2008; Kaduna.

Iken, J.E.; Amusa, N.A. & Obatolu, V.O. (2002): Nutrient composition and weight evaluation of some newly developed maize varieties in Nigeria.- The Journal of Food Technology in Africa, 7: 27-29.

Isichei, A.O. & Muoghalu, J.I. (1992): The effects of tree canopy cover on soil fertility in a Nigerian savanna.- Journal of Tropical Ecology, 8: 329-338.

Isichei, A.O.; Morton, A.J. & Ekeleme, F. (1990): Mineral nutrient flow from an inselberg in south-western Nigeria.- Journal of Tropical Ecology, 6: 479-492.

Islam, M.S. (2008): Soil fertility history, present status and future scenario in Bangladesh.- Bangladesh Journal of Agriculture and Environment, 4: 129-151.

ISRIC (1964): Soil map of Nigeria, 1:5000000; Wageningen.

IUSS Working Group WRB (2006a): World Reference Base for Soil Resources. A framework for international classification, correlation and communication.- 1. ed.; 128 pp.; Rome.

IUSS Working Group WRB (2006b): Guidelines for soil description.- 4. ed.; 97 pp; Rome.

Jacobs, L.W. [Ed.] (1989): Selenium in agriculture and the environment.- 1. ed.; 233 pp.; Madison.

Järup, L. [Ed.] (1998): Health effects of cadmium exposure. A review of the literature and a risk estimate.- Scandinavian Journal of Work, Environment & Health, 24: 1-52.

Jaiyeoba, I.A. (2003): Changes in soil properties due to continuous cultivation in Nigerian semiarid savannah.- Soil & Tillage Research, 70: 91-98.

Jaiyeoba, I.A. (1997): An assessment of soil fertility restoration under fallow in Nigerian savannah.- Soil Use and Management, 13: 163-164.

Jaiyeoba, I.A. (1995): Variation of soil chemical properties over Nigerian savanna.- Singapore Journal of Tropical Geography, 16: 141-157.

Jakob, F.; Seefried, L.; Kitz, C.; Stich, A.; Sponholz, B.; Raab, P. & Ebert, R. (2010): Trace elements and bone.- In: Burckhardt, P.; Dawson-Hughes, B. & Weaver, C. [Eds.]: Nutritional Influences on Bone Health: 81-86; London.

Jarrett, H.R. (1949): Major natural regions of the Gambia.- Scottish Geographical Magazine, 65: 140-144.

Jatau, B.S.; Bajeh, I. & Innocent, S. (2008): Trace metals in surface and subsurface water in Kaduna south industrial area, north-central Nigeria.- Research Journal of Applied Sciences, 3: 81-87.

Jelliffe, D.B. (1951): Clinical rickets in Ibadan.- Transactions of the Royal Society of Tropical Medicine, 45: 119-126.

Jha, S.K.; Nayak, A.K.; Sharma, Y.K.; Mishra, V.K. & Sharma, D.K. (2008): Fluoride accumulation in soil and vegetation in the vicinity of brick fields.- Bulletin of Environmental Contamination and Toxicology, 80: 369-373.

Johnson, C.C.; Fordyce, F.M. & Rayman, M.P. (2010): Factors controlling the distribution of selenium in the environment and their impact on health and nutrition.- Proceedings of the Nutrition Society, 69: 119-132.

Johnson, C.C.; Ge, X.; Green, K.A. & Liu, X. (2000): Selenium distribution in the local environment of selected villages of the Keshan disease belt, Zhanggijakou District, Hebei Province, People's Republic of China.- Applied Geochemistry, 15: 385-401.

Jones, B.F.; Eugster, H.P. & Reitig, S.L. (1977): Hydrochemistry of the Lake Magadi basin, Kenya.- Geochimica et Cosmochimica Acta, 41: 53-72.

Jones, H.L.; Jammeh, L.; Ebrim, A.; Bikwe, M.; Owens, S.; Fulford, A.J.; Pettifor, J.M. & Prentice, A. (2009): The prevalence of rickets-like bone deformities in rural Gambian children.- Bone, 45: S83-S84.

Jones, K.C. & Bennett, B.G. (1986): Exposure of man to environmental aluminium. An exposure commitment assessment.- The Science of the Total Environment, 52: 65-82.

Jones, M.J. & Wild, A. (1975): Soils of the West African savanna. The maintenance and improvement of their fertility.- 1. ed.; 245 pp.; Slough.

Jordan, R.A.; Makovic, L. & Gaengler, P. (2008): Fluoride availability from natural resources in The Gambia – implications for oral health care.-International Dental Journal, 58: 237-242.

Junge, B. & Skowronek, A. (2007): Genesis, properties, classification and assessment of soils in Central Benin, West Africa.- Geoderma, 139: 357-370.

Juo, A.S.R.; Ayanlaja, S.A. & Ogunwale, J.A. (1976): An evaluation of cation-exchange capacity measurements for soils in the tropics.- Communications in Soil Science and Analysis, 7: 751-761.

Kabata-Pendias, A. & Mukherjee, A.B. (2007): Trace elements from soil to human.- 1. ed.; 550 pp.; Berlin.

Kabir, M.L.; Rahman, M.; Talukder, K.; Rahman, A.; Hossain, Q.; Mostafa, G.; Mannan, M.A.; Kumar, S. & Chowdhury, A.T. (2004): Rickets among children of a coastal area of Bangladesh.- Mymendsingh Medical Journal, 13: 53-58.

Kabir, M.L. (1998): Report of the prevalence study on rickets in children of Chakaria.- 1. ed.; 48 pp.; Dhaka.

Kaduna State Geological Survey (2008): Geological map; 1:400000; Kaduna.

Kageni, B. (2009): Rickets no longer a disease of the past in Naivasha.- http://ourkenyanstories.blogspot.com/2009/08/rickets-no-longer-disease-of-past-in.html [2012/10/13].

Kang, B.T. & Osiname, O.A. (1985): Micronutrient problems in tropical Africa.- Fertilizer Research, 7: 131-150.

Kanwar, J.S. & Youngdahl, L.J. (1985): Micronutrient needs of tropical food crops.- In: Vlek, P.L.G. [Ed.]: Micronutrients in tropical food production: 43-67; Dordrecht.

Kamprath, E.J. (1970): Exchangeable aluminium as a criterion for liming leached mineral soils.- Soil Science Society of America Proceedings, 34: 252-254.

Karim, F.; Chowdhury, A.M.R. & Gani, M.S. (2003): Rapid assessment of the prevalence of lower limb clinical rickets in Bangladesh.- Public Health, 117: 135-144.

Katyal, J.C. & Vlek, P.L.G. (1985): Micronutrient problems in tropical Asia.- Fertilizer Research, 7: 69-94.

Kazantzis, G. (2004): Cadmium, osteoporosis and calcium metabolism.- Biometals, 17: 493-498.

Keating, E.M.; Fischer, P.R.; Pettifor, J.M.; Pfitzner, M.; Isichei, C.O. & Thacher, T.D. (2011): The effect of calcium supplementation on blood lead levels in Nigerian children.- The Journal of Pediatrics, 159: 845-850.

Kimuna, S.R. & Makiwane, M. (2007): Older people as resources in South Africa. Mpumalanga households.- Journal of Ageing & Social Policy, 19: 97-114.

Kinniburgh, D.G. & Smedley, P.L. [Eds.] (2001): Arsenic contamination of groundwater in Bangladesh.- 2. vol.; 289 pp.; Keyworth.

Kitz, C.; Stich, A.; Ebert, R.; Jakob, F.; Raab, P. & Sponholz, B. (2009): Rickets in Nigeria. Do geological and genetic factors play a role besides extreme calcium deficiency?- Flug und Reisemedizin, 16: 76-80.

Klaasen, R.A.; Douma, S. & Rencz, A.N. (2010): Environmental and human health risk assessment for essential trace elements. Considering the role for geosciences.- Journal of Toxicology and Environmental Health, 73: 242-252.

Klein, G.L. (1990): Nutritional aspects of aluminium toxicity.- Nutritional Research Reviews, 3: 117-141.

Knez, M. & Graham, R.D. (2013): The impact of micronutrient deficiencies in agricultural soils and crops on the nutritional health of humans.- In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology: 517-533; Dordrecht.

Konishi, Y.; Yagyu, K.; Kinebuchi, H.; Saito, N.; Yamaguchi, T. & Ohtsuki, Y. (1996): Chronic effect of aluminium ingestion on bone in calcium-deficient rats.- Pharmacology & Toxicology, 78: 429-434.

Kparmwang, T. & Malgwi, W.B. (2009): Quality of some fertilizer samples in the Nigerian market (2002-2007).- Nigerian Journal of Soil Science, 19: 34-40.

Krewski, D.; Yokel, R.A.; Nieboer, E.; Borchelt, D.; Cohen, J.; Harry, J.; Kacew, S.; Lindsay, J.; Mahfouz, A.M. & Rondeau, V. (2009): Human health risk assessment for aluminium oxide and aluminium hydroxide.- Journal of Toxicology and Environmental Health, Part B: Critical Reviews, 10: 1-337.

Kröner, A.; Ekwueme, N. & Pidgeon, R.T. (2001): The oldest rocks in western Africa: shrimp zircon age for early Archean migmatitic orthogneiss at Kaduna, northern Nigeria.- The Journal of Geology, 109: 399-406.

Kuhnlein, H.V. & Receveur, O. (1996): Dietary change and traditional food systems of indigenous people. Annual Review of Nutrition, 16: 417-442.

Laditan, A.A. & Adeniyi, A. (1975): Rickets in Nigerian children: response to vitamin D. Journal of Tropical Medicine and Hygiene, 78: 206-209.

Lal, R. (2009): Soil degradation as a reason for inadequate human nutrition.- Food Security, 1: 45-57.

Lal, R. (1997): Long-term tillage and maize monoculture effects on a tropical Alfisol in western Nigeria, II. Soil chemical properties.- Soil and Tillage Research, 42: 161-174.

Lag, J. (1990): Geomedicine.- 1. ed.; 288 pp.; Boca Raton.

Laing, du G. (2010): Analysis and fractionation of trace elements in soils.- In: Hooda, P. [Ed.]: Trace elements in soils: 54-80; Chichester.

Landon, J.R. (1991): Booker tropical soil manual. A handbook for soil survey and agricultural land evaluation in the tropics and subtropics.- 1. ed.; 475 pp.; Essex.

Larsen, S. & Widdowson, A.E. (1971): Soil fluorine.- Journal of Soil Science, 22: 210-222.

Larsson, M.; Rossander-Hulthen, L.; Sandstrom, B. & Sandberg, A.S. (1996): Improved zinc and iron absorption from breakfast meals containing malted oats with reduced phytate content.- British Journal of Nutrition, 76: 677-688.

Lemuel, M.M. (2012): Pedogenesis of a lithosequence in the northern guinea savanna of Kaduna State, Nigeria.- 249 pp.; Ahmadu Bello University Zaria, Nigeria [Doctoral thesis].

Li, S.; Li, W.; Yang, L. & Xirao, R. (2009): Soil selenium concentration and Kashin-Beck disease prevalence in Tibet, China.- Frontiers of Environmental Science & Engineering in China, 3: 62-68.

Lindsay, W.L. (1979): Chemical equilibria in soils. - 1. ed.; 449 pp.; New York.

Liu, Z. (2005); Studies on rickets and osteomalacia in Bactrian camels (Camelus bactrianus).- The Veterinary Journal, 169: 444-453.

Loganathan, P.; Hedley, M.J.; Wallace, G.C. & Roberts, A.H.C. (2001): Fluoride accumulation in pasture forages and soils following long-term applications of phosphorus fertilizer.- Environmental Pollution, 115: 275-282.

Lokkett, C.T.; Calvert, C.C. & Grivetti, L.E. (2000): Energy and micronutrient composition of dietary and medicinal wild plants consumed during drought. Study of rural Fulani, northeastern Nigeria.- International Journal of Food Sciences and Nutrition, 51: 195–208.

Lombin, L.G. (1979): Evaluation of the magnesium supplying powers of the Nigerian savannah soils.- Soil Science and Plant Nutrition, 25: 477-492.

Long, J.K.; Murphy, S.P.; Weiss, R.E.; Nyerere, S.; Bwibo, N.O. & Neumann, C.G. (2011): Meat and milk intakes and toddler growth. A comparison feeding intervention of animal-source foods in rural Kenya.- Public Health Nutrition, 15: 1100-1107.

Lowe, N.M.; Fraser, W.D. & Jackson, M.J. (2002):

Is there a potential therapeutic value of copper and zinc for osteoporosis?- Proceedings of the Nutrition Society, 61: 181-185.

Lyngsie, G.; Awadzi, T. & Breunig-Madsen, H. (2011): Origin of harmattan dust settled in northern Ghana. Long transported or local dust?- Geoderma, 167-168: 351-359.

Ma, G.; Li, Y.; Jin, Y.; Zhai, F.; Kok, F.J. & Yang, X. (2007): Phytate intake and molar ratios of phytate to zinc, iron and calcium in the diets of people in China.- European Journal of Clinical Nutrition, 61: 368–374.

Mahre, M.Y.; Akan, J.C.; Moses, E.A. & Ogugbuaja, V.O. (2007): Pollution indicators in River Kaduna, Kaduna State, Nigeria.- Trends in Applied Science Research, 2: 304-311.

Maithani, P.G.; Gujar, R.; Banerjee, R.; Balaji, B.K.; Ramachandran, S. & Singh, R. (1998): Anomalous fluoride in groundwater from the western part of Sirohi District Rajasthan and its crippling effects on human health.- Current Science, 74: 773-777.

Malgwi, W.B. & Abu, S.T. (2011): Variation in some physical properties of soils formed on a hilly terrain under different land-use types in Nigerian savanna.- International Journal of Soil Sciences, 6: 150-163.

Malomo, S. (1983): Weathering and weathering products of Nigerian rocks. Engineering implications.- In: Ola, S.A. [Ed.]: Tropical soils of Nigeria in engineering practice: 39-60; Rotterdam.

Mamo, T.; Richter, C. & Heiligtag, B. (2002): Phosphorus availability studies on ten Ethiopian Vertisols.- Journal of Agriculture and Rural Development in the Tropics and Subtropics, 103: 177-183.

Manna, F.; Hussain, T.; Alli, I. & Igbal, P. (1987): Effect of cooking on phytic acid content and nutritive value of Pakistani peas and lentils.- Food Chemistry, 2: 81-87.

Manyong, V.M.; Makinde, K.O.; Sanginga, N.; Vanlauwe, B. & Diels, J. (2001): Fertiliser use and definition of farmer domains for impact-oriented research in the northern guinea savanna of Nigeria.- Nutrient Cycling in Agroecosystems, 59: 129-141.

Marasas, W.F.O. & Rensburg, van S.J. (1986): Mycotoxicological investigations on maize and groundnuts from the endemic area of Mseleni joint disease in Kwazulu.- South African Medical Journal, 69: 369-374.

Marfo, E.K.; Simpson, B.K.; Idowu, J.S. & Oke, O.L. (1990): Effect of local food processing on phytate levels in cassava, cocoyam, yam, maize, sorghum, rice, cowpea and soybean.- Journal of Agricultural and Food Chemistry, 38: 1580-1585.

Marius, C. (1982): Acid sulphate soils of the mangrove area of Senegal and Gambia.- In: Dost, H. & Breemen, van N. [Eds.]: Proceedings of the Bangkok symposium on acid sulphate soils. Second international symposium on acid sulphate soils, Bangkok, Thailand, January 18-24; 1981: 103-136; Wageningen.

Markert, B.; Kayser, G.; Korhammer, S. & Oehlmann, J. (2000): Distribution and effects of trace substances in soil, plants and animals. In: Markert, B. & Friese, K. [Eds.]: Trace elements in the environment: 3-33; Amsterdam.

Matheis, G. & Pearson, M.J. (1982): Mineralogy and geochemical dispersion in lateritic soil profiles of northern Nigeria.- Chemical Geology, 35: 129-145.

Mathee, A.; Schirnding, von Y.E.R; Levin, J.; Ismail, A.; Huntley, R. & Cantrell, A. (2002): A survey of blood lead levels among young Johannesburg school children.- Environmental Research, 90: 181-184.

Mathieu, F.; Suetens, C.; Begaux, F.; Maertelaer, de V. & Hinsenkamp, M. (2001): Effects of physical therapy on patients with Kashin-Beck disease in Tibet.- International Orthopaedics, 25: 191-193.

Maydell, H.J. (1990): Trees and shrubs of the Sahel. Their characteristics and uses. 1. ed.; 525 pp.; Weikersheim.

McCance, R.A. & Walsham, C.M. (1948): The digestibility and absorption of the calories, proteins, purines, fat and calcium in wholemeal wheaten bread.- British Journal of Nutrition, 2: 26-41.

McCance, R.A. & Widdowson, E.M. (1935): Phytin in human nutrition.- Biochemical Journal, 29: 2694-2699.

McGregor, I.A. & Smith, D.A. (1952): A health, nutrition and parasitological survey in a rural village (Keneba) in West Kiang Gambia.- Transactions of the Royal Society of Tropical Medicine, 46:403-27.

McMichael, A.J. (2000): The urban environment and health in a world of increasing globalisation. Issues for developing countries.- Bulletin of the World Health Organization, 78: 1117-1126.

McTainsh, G. (1984): Harmattan dust deposition in northern Nigeria.- Nature, 286: 587-588.

Mebrahatu, S.; Pelletier, D. & Pinstrup-Andersen, P. (1995): Agriculture and nutrition.- In: Pinstrup-Andersen, P.; Pelletier, D. & Alderman, A. [Eds.]: Child growth and nutrition in developing countries. Priorities for action: 221-242; Ithaca.

Meek, C.K. (1971): The northern tribes of Nigeria: an ethnographical account of the northern provinces of Nigeria together with a report on the 1921 decennial census.- 1. part; 276 pp.; London.

Meiwes, K.-J.; König, N.; Khanna, P.K.; Prenzel, J. & Ulrich, B. (1984): Chemische Untersuchungsverfahren für Mineralboden, Auflagehumus, und Wurzeln zur Charakterisierung und Bewertung der Versauerung in Waldböden.- Berichte des Forschungszentrums Waldökosysteme/ Waldsterben, 7: 1-67.

Menkir, A. (2008): Genetic variation for grain mineral content in tropical-adapted maize inbred lines.- Food Chemistry, 110: 454-464.

Meredith, R.M. (1965): A review of the responses to fertilizers of the crops of northern Nigeria.- Samaru Miscellaneous Paper, 4: 1-8.

Meybeck, M.; Lo, H.M.; Cauwet, G. & Gac, J.Y. (1987): Geochemistry of the Sahelian Gambia River during the 1983 high-water stage.- Mitteilungen Geologisches Paläontologisches Institut Universität Hamburg, 64: 461-473.

Mibei, E.K.; Ojijo, N.K.O.; Karanja, S.M. & Kinyua, J.K. (2011): Compositional attributes of the leaves of some indigenous African leafy vegetables commonly used in Kenya.- Annals. Food Science and Technology, 12:146-154.

Millot, J. (1941): Observations sur le rachitisme dans la race noir.-Comptes Rendus de l'Académie de Sciences, 213: 370.

Millis, P.R.; Ramsey, M.H. & John, E.A. (2004): Heterogeneity of cadmium concentration in soil as a source of uncertainty in plant uptake and its implications for human health risk assessment.- Science of the Total Environment, 326: 49-53.

Møberg, J.P. & Esu, I.E. (1991): Characteristics and composition of some savanna soils in Nigeria.- Geoderma, 48: 113-129.

Møberg, J.P.; Esu, I.E. & Malgwi, W.B. (1991): Characteristics and constituent composition of Harmattan dust falling in northern Nigeria.- Geoderma, 48: 73-81.

Mokwunye, U. (1979): Phosphorus needs of soils and crops of the savanna zones of Nigeria.- Phosphorus in Agriculture, 76: 87-95.

Moore, D.M. & Reynolds, R.C. (1997): X-ray diffraction and the identification and analysis of clay minerals.- 2. ed.; 378 pp.; Oxford.

Moreno, T.; Querol, X.; Castillo, S.; Alastuey, A.; Cuevas, E.; Herrmann, L.; Mounkaila, M.; Elvira, J. & Gibbons, W. (2006): Geochemical variations in aeolian mineral particles from the Sahara–Sahel dust corridor.- Chemosphere, 65: 261-270.

Moreno-Reyes, R.; Egrise, D.; Neve, J.; Pasteels, J.L. & Schoutens, A. (2001): Selenium-deficiency induced growth retardation is associated with impaired bone metabolism and osteopenia.- Journal of Bone Mineral Research, 16: 1556-1563.

Mortimore, M.; Essiet, E.U. & Patrick, S. (1990): The nature, rate and effective limits of intensification in the small holder farming system of the Kano close-settled zone.- 1. ed.; 198 pp.; Ibadan.

Mpenyana-Monyatsi, L.; Onyango, M.S. & Momba, M.N.B. (2012): Groundwater quality in a South African rural community: a possible threat to public health.- Polish Journal of Environmental Studies, 21: 1349-1358.

Msomekela, M.; Manji, K.; Mbise, R.L.; Razerna, R. & Makwaya, C. (1999): A high prevalence of metabolic bone disease in exclusively breast-fed very low birthweight infants in Dar es Salaam, Tanzania.- Annals of Tropical Paediatrics, 19: 337-344.

MTSAFRF (1985): Topographical map; 1:200000; Kaduna.

Mughal, Z. (2012): Resurgence of Vitamin-D-deficiency rickets in the UK.- Endocrine Abstracts, 28: 7.

Muhe, L.; Lulseged, S.; Mason, K.E. & Simoes, E.A. (1997): Case-control study of the role of nutritional rickets in the risk of developing pneumonia in Ethiopian children.- The Lancet, 349: 1801-1804.

Munkholm, L.J.; Esu, I.E. & Møberg, J.P. (1993): Trace elements in some northern Nigerian soils.- Communications in Soil Science and Plant Analysis, 24: 657-672.

Munsell (2000): Munsell Soil Colour Chart.- Revised washable ed.; 9 pp.; New Windsor.

Muraya, J.W. (2012): Wilting in bloom. Rickets cases worry medics in Naivasha.- http://www.africanewswire.net/story.php?title=wilting-in-bloom-rickets-cases-worry-medics-in-naivasha

[2012/10/13].

Murphy, P.K. (1981): The foods and cooking of rural Gambia.-In: Davidson, A. [Ed.]: National and regional styles of cooking. Proceedings of the Oxford Symposium: 290-302; London.

Mwangi, W.M. (1997): Low use of fertilizers and low productivity in sub-Saharan Africa.- Nutrient Cycling in Agroecosystems, 47: 135-147.

Nabhan, H. (2000a): Land degradation and food security.- In: Adepetu, J.A.; Nabhan, H. & Osinubi, A. [Eds.]: Simple soil, water and plant testing techniques for soil resource management. Proceedings of a training course held in Ibadan, Nigeria, 16-27 September 1996: 111-115; Rome.

Nabhan, H. (2000b): Soil-tests in relation to fertilizer recommendations.- In: Adepetu, J.A.; Nabhan, H. & Osinubi, A. [Eds.]: Simple soil, water and plant testing techniques for soil resource management. Proceedings of a training course held in Ibadan, Nigeria, 16-27 September 1996: 99-104; Rome.

Namgung, R. & Tsang, R.C. (2000): Factors affecting newborn bone mineral content. In utero effects on newborn bone mineralization.- Proceedings of the Nutrition Society, 59: 55-63.

National Research Council (1980): Recommended dietary allowances.- 10. ed.; 302 pp.; Washington D.C.

Ndiokwere, C.L. & Ezihe, C.A. (1990): The occurrence of heavy metals in the vicinity of industrial complexes in Nigeria.- Environment International, 16: 291-295.

Njoku, B.O.; Enwezor, W.O. & Onyenakwe, B.I. (1987): Calcium deficiency identified as an important factor limiting maize growth in acid Ultisols of eastern Nigeria.- Fertilizer Research, 14: 113-123.

Noda, M.; Yasuda, M. & Kitagawa, M. (1991): Iron as a possible aggravating factor for osteopathy in Itai-Itai disease, a disease associated with chronic cadmium intoxication.- Journal of Bone and Mineral Research, 6: 245-255.

Nriagu, J.; Oleru, N.T.; Cudjoe, C. & Chine, A. (1997): Lead poisoning of children in Africa, III. Kaduna, Nigeria.- The Science of the Total Environment, 197: 13-19.

Nriagu, J.O. (1992): Toxic metal pollution in Africa.- The Science of the Total Environment, 121: 1-37.

Nwaedozie, G.C.; Agbaji, E.B. & Nwaedozie, J.M. (2011): Evaluation of some trace metals concentrations in bank sediments of River Kaduna, Nigeria.- Academic Research International, 1: 410-418.

Nwoke, O.C.; Vanlauwe, B.; Diels, J.; Sanginga, N. & Osonubi, O. (2004): Nutrient Cycling in Agroecosystems, 69: 127-141.

Nyakundi, P.M.; Kinuthia, D.W. & Orinda, D.A. (1994): Clinical aspects and causes of rickets in a Kenyan population.- East African Medical Journal, 71: 536-542.

Obaje, N.G. (2009): Geology and Minerals of Nigeria. Lecture notes in earth sciences.- 1. ed.; 221 pp.; Heidelberg.

Obiora, S.C. (2012): Chemical characterization and tectonic evolution of hornblende-biotite granitoids from the Precambrian basement complex around Ityowanye and Katsina-Ala, south-eastern Nigeria.- Journal of Mining and Geology, 48: 13-29.

Odeyemi, O. & Ogunseitan, O.A. (1985): Petroleum industry and its pollution potential in Nigeria.- Oil & Petrochemical Pollution, 2: 223-229.

Odeyemi, O. (1980): A review on the orogenic events in the Precambrian basement of Nigeria, West Africa.- Geologische Rundschau, 70: 897-909.

Odunze, A.C.; Iwuafor, E.N.O. & Chude, V.O. (2002): Maize/herbaceous legume intercrops and soil properties in the northern guinea savanna zone, Nigeria.- Journal of Sustainable Agriculture, 20: 15-25.

Özgür, S.; Sümer, H. & Koçoglu, G. (1996): Rickets and soil strontium.- Archives of Disease in Childhood, 75: 524-526.

Oginni, L.M.; Sharp, C.A.; Badru, C.S.; Davie, M.W. & Worsfold, M. (2003): Radiological and biochemical resolution of nutritional rickets with calcium.- Archives of Diseases in Childhood, 88: 812-817.

Oginni, L.M.; Worsfold, M.; Sharp, C.A.; Oyelami, O.A.; Powell, D.E. & Davie, M.W.J. (1996): Plasma osteocalcin in healthy Nigerian children and in children with calcium-deficiency rickets.- Calcified Tissue International, 59: 424-427.

Ogoshi, K.; Moriyama, T. & Nanzai, Y. (1989): Decrease in the mechanical strength of bones of rats administered cadmium.- Archives of Toxicology, 63: 320-324.

Ojanuga, A.G. (1979): Clay mineralogy of soils in the Nigerian tropical savanna regions.- Soil Science Society of America Journal, 43: 1237-

1242.

O'Kelly, M.E. (2007): The impact of accessibility on the geography of crop production. A re-examination of the Illinois and Michigan canal using GIS.- Annals of the Association of American Geographers, 97: 49-63.

Okonofua, F.; Gill, D.S.; Alabi, Z.O.; Thomas, M.; Bell, J.L. & Dandona, P. (1991): Rickets in Nigerian children: A consequence of calcium malnutrition.- Metabolism, 40: 209-213.

Okunola, O. J.; Uzairu, A. & Ndukwe, G. (2010): Levels of trace metals in soil and vegetation along major and minor roads in metropolitan city of Kaduna, Nigeria.- African Journal of Biotechnology, 6: 1703-1709.

Olivier, M.A. (1997): Soil and human health. A review.- European Journal of Soil Science, 48: 573-592.

Olaofe, O. & Sanni, C.O. (1988): Mineral contents of agricultural products.- Food chemistry, 30: 73-77.

Oluwatosin, G.A.; Adeyolanu, O.D.; Dauda, T.O. & Akinbola, G.E. (2008): Levels and geochemical fractions of Cd, Pb and Zn in valley bottom soils of some urban cities in south-western Nigeria.- African Journal of Biotechnology, 7: 3455-3465.

Omdahl, J.L. & DeLuca, H.F (1971): Strontium induced rickets: metabolic basis.- Science, 174: 949-951.

Onwumere, B.G. & Oladimeji, A.A. (1990): Accumulation of metals and histopathology in oreochromis niloticus exposed to treated NNPC Kaduna (Nigeria) petroleum refinery effluent.- Ecotoxicology and Environmental Safety, 19: 123-134.

Onyiriuka, A.; Abiodun, P. & Onyiriuka, F. (2012): Nutritional rickets in childhood: retrospective assessment of clinical data of forty five cases seen in a Nigerian tertiary healthcare institution.- Current Pediatric Research, 16: 129-133.

Oramasionwu, G.E.; Thacher, T.D.; Pam, S.D.; Pettifor, J.M. & Abrams, S.A. (2008): Adaptation of calcium absorption during treatment of nutritional rickets in Nigerian children.- British Journal of Nutrition, 100: 387-392.

Oyatsi, D.P.; Musoke, R.N. & Wasunna, A.O. (1999): Incidence of rickets of prematurity at Kenyatta National Hospital, Nairobi.- East African Medical Journal, 76: 63-66.

Oyemade, G.A.A. (1975): Aetiological factors in genu valga, vara and varovalga in Nigerian children.- Journal of Tropical Paediatrics, 21: 167-172.

Oyewale, A.O. & Funtua, I.I. (2002): Lead, copper and zinc levels in soils along Kaduna-Zaria Highway, Nigeria.- Global Journal of Environmental Sciences, 1: 7-14.

Oyo, O.M. (1996): Geological map of Nigeria, 1:200000; Abuja.

Ozsvath, D.L. (2009): Fluoride and environmental health. A review.- Reviews in Environmental Science and Biotechnology, 8: 59-79.

Pagel, H. (1981): Grundlagen des Nährstoffhaushaltes tropischer Böden.- 1. ed.; 191 pp.; Berlin.

Pai, B. (2011): Understanding rickets.- Paediatrics and Child Health, 21: 315-321.

Paul, E.D.; Gimba, C.E.; Kagbu, J.A.; Ndukwe, G.I. & Okibe, F.E. (2011): Spectrometric determination of fluoride in water, soil and vegetables from the precinct of River Basawa, Zaria, Nigeria.- Journal of Basic and Applied Chemistry, 1: 33-38.

Peterson, C.J.; Johnson, V.A. & Mattern, P.J. (1986): Influence of cultivar and environment on mineral and protein concentrations of wheat flour, bran and grain.- Cereal Chemistry, 63: 183-186.

Pettifor, J.M.; Fischer, P.R.; Thacher, T.D.; Arnaud, J. & Meissner, C.A. (2008): Dietary calcium deficiency & rickets.- Indian Journal of Medical Research, Correspondence, 128: 673-676.

Pettifor, J.M.; (2004): Nutritional rickets. Deficiency of vitamin D, calcium or both?- The American Journal of Clinical Nutrition, 80: 1725S-1729S.

Pettifor, J.M.; Prentice, A. & Cleaton-Jones, P. (2003): The skeletal system.- In: Gibney, M.J.; MacDonald, I. & Roche, H.M. [Eds.]: Nutrition and Metabolism: 246-283; Oxford.

Pettifor, J.M.; Ross, F.P.; Travers, R.; Glorieux, F.H. & DeLuca, H.F. (1981): Dietary calcium deficiency: a syndrome associated with bone deformities and elevated serum 1.25 –dihydroxyitamin D concentrations.- Metabolic Bone Disease and Related Research, 2: 301-305.

Pettifor, J.M.; Ross, P.; Moodley, G. & Shuenyane, E. (1979): Calcium deficiency in rural black children in South Africa: a comparison between rural and urban communities.- American Journal of Clinical Nutrition, 32: 2477-2483.

Pettifor, J.M.; Ross, P.; Wang, J.; Moodley, G. & Couper-Smith, J. (1978): Rickets in children of rural origin in South Africa: Is low dietary calcium a factor?- The Journal of Pediatrics, 92: 320-324.

Pettijohn, F.J. (1975): Sedimentary rocks.- 2. ed.; 718 pp.; New York.

Pfeiffer, S. & Crowder, C. (2004): An ill child among Mid-Holocene foragers of Southern Africa.- American Journal of Physical Anthropology, 123: 23-29.

Pfitzner, M.A.; Thacher, T.D.; Pettifor, J.M.; Zoakah, A.I.; Lawson, J.O. & Fischer, P.R. (2001): Prevalence of elevated blood lead levels in Nigerian children.- Ambulatory Child Health, 6: 115-123.

Pfitzner, M.A.; Thacher, T.D.; Pettifor, J.M.; Zoakah, A.I.; Lawson, J.O.; Isichei, C.O. & Fischer, P.R. (1998): Absence of vitamin D deficiency in young Nigerian children.- The Journal of Pediatrics, 133: 740-744.

Phillips-Howard, K.D. & Lyon, F. (1994): Agricultural intensification and the threat to soil fertility in Africa. Evidence from the Jos Plateau, Nigeria.- The Geographical Journal, 160: 252-265.

Pickering, W.F. (1985): The mobility of soluble fluoride in soils.- Environmental Pollution, 9: 281-308.

Plant, J.A.; Baldock, J.W. & Smith, B. (1996): The role of geochemistry in environmental and epidemiological studies in developing countries.- In: Appleton, J.D.; Fuge, R. & McCall, G.J.H. [Eds.]: Environmental Geochemistry and Health: 7-22; London.

Plumlee, G.S.; Durant, J.T.; Morman, S.A.; Neri, A.; Wolf, R.E.; Dooyema, C.A.; Hageman, P.L.; Lowers, H.A.; Fernette, G.L.; Meeker, G.P.; Benzel, W.M.; Driscoll, R.L.; Berry, C.J.; Crock, J.G.; Goldstein, H.L.; Adams, M.; Bartrem, C.L.; Tirima, S.; Behbod, B.; Lindern, von I. & Brown, M.J. (2013): Linking geological and health sciences to assess childhood lead poisoning from artisanal gold mining in Nigeria.- Environmental Health Perspectives, 121: 744-750.

Pooley, J. (1999): Is the poor growth of maize in the Maputaland area of South Africa caused by mineral deficiencies?- http://www.geocities.ws/samaize/bio1.html [2013/07/27].

Pooley, J. (1997): Nutrient deficiencies in soils of the Mseleni area, Kwazulu-Natal.- 180 pp.; University of Cape Town, South Africa [Master thesis].

Preez, du J.W. & Barber, W. (1965): The distribution and chemical quality of groundwater in northern Nigeria.- 1. ed.; 93 pp.; Kaduna.

Prentice, A. (2013): Nutritional rickets around the world.- The Journal of Steroid Biochemistry and Molecular Biology, 136: 201-206.

Prentice, A.; Ceesay, M.; Nigdikar, S.; Allen, S.J. & Pettifor, J.M. (2008): FGF23 is elevated in Gambian children with rickets.- Bone, 42: 788-97.

Prentice, A.; Schoenmakers, I.; Laskey, M.A.; Bono, de S.; Ginty, F. & Goldberg, G.R. (2006): Symposium on nutrition and health in children and adolescents. Session 1: Nutrition in growth and development.- Proceedings of the Nutrition Society, 65: 348-360.

Prentice, A. & Bates, C.J. (1994): Adequacy of dietary mineral supply for human bone growth and mineralization.- European Journal of Clinical Nutrition, 48: S161-S177.

Prentice, A.; Laskey, A.M.; Shaw, J.; Hudson, G.J.; Day, K.C.; Jarjou, L.M.A.; Dibba, B. & Paul, A.A. (1993): The calcium and phosphorus intakes of rural Gambian women during pregnancy and lactation.- British Journal of Nutrition, 69: 885-896.

Putthacharoen, S.; Howeler, R.H.; Jantawat, S. & Vichukit, V. (1997): Nutrient uptake and soil erosion losses in cassava and six other crops in a Psamment in eastern Thailand.- Field Crops Research, 57: 113-126.

Pypers, P.; Loon, van L.; Diels, J.; Abaidoo, R.; Smolders, E. & Merckx, R. (2006): Plant available P for maize and cowpea in P-deficient soils from the Nigerian northern guinea savanna. Comparison of E- and L-levels.- Plant and Soil, 283: 251-264.

Raboy, V. (2000): Low-phytic acid grains.- Food and Nutrition Bulletin, 21: 423-427.

Rader, J.I.; Baylink, D.J.; Hughes, M.R.; Safilian, E.F. & Haussler, M.R. (1979): Calcium and phosphorus deficiency in rats. Effects on PTH and 1.25 dihydroxyvitamin D_3.- American Journal of Physiology, Endocrinology and Metabolism, 236: E118-E122.

Rahaman, M.A. & Malomo, S. (1983): Sedimentary and crystalline rocks of Nigeria.- In: Ola, S.A. [Ed.]: Tropical soils of Nigeria in engineering practice: 17-38; Rotterdam.

Rahaman, M.A. & Ocan, O. (1978): On relationships in the Precambrian migmatitic gneisses of Nigeria.- Nigerian Journal of Mining and Geology, 15: 23-32.

Raji, B.A.; Malgwi, W.B.; Berding, F.R. & Chude, V.O. (2011): Integrating indigenous knowledge and soil science approaches to detailed soil survey in Kaduna State, Nigeria.- Journal of Soil Sciences and Environmental Management, 2: 66-73.

Rayment, G.E. & Lyons, D.J. (2011): Soil chemical methods. Australasia.- 1. ed.; 495 pp.; Collingwood.

Rebertus, R.A.; Weed, S.B. & Buol, S.W. (1986): Transformation of biotite to kaolinite during saprolite-soil weathering.- Soil Science Society of America Journal, 50: 810-819.

Reeuwijk, van L.P. (2002): Procedures for soil analyses.- 6. ed.; 120 pp.; Wageningen.

Reimann, C. & Caritat, de P. (1998): Chemical elements in the environment. Fact sheets for the geochemist and environmental scientist.- 1. ed.; 397 pp.; Berlin.

Reinhold, J.G.; Faradji, B.; Abadi, P. & Ismail-Beigi, F. (1979): Decreased absorption of calcium, magnesium, zinc and phosphorus by humans due to increased fibre and phosphorus consumption as wheat bread.- The Journal of Nutrition, 106: 493-503.

Reinhold, J.G. (1971): High phytate content of rural Iranian bread. A possible cause of human zinc deficiency.- The American Journal of Clinical Nutrition, 24: 1204-1206.

Rensburg, van H.G.; Claassens, A.S. & Beukes, D.J. (2009): Relationships between soil buffer capacity and selected soil properties in a resource-poor farming area in the Mpumalanga Province of South Africa.- South African Journal of Plant and Soil, 26: 237-243.

Rengel, Z. (2004): Aluminium cycling in the soil-plant-animal-human continuum.- Biometals, 17: 669-689.

Rengel, Z.; Batten, G.D. & Crowley, D.E. (1999): Agronomic approaches for improving the micronutrient density in edible portions of field crops.- Field Crops Research, 60: 27-40.

Reuter, D.J. & Robinson, J.B. (1997): Plant analysis. An interpretation manual.- 2. ed.; 572 pp.; Collingwood.

Ridder, de N.; Breman, H.; Keulen, van H. & Stomph, T.J. (2004): Revisiting a cure against land hunger. Soil fertility management and farming system dynamics in the West African Sahel.- Agricultural Systems, 80: 109-131.

Ritchey, K.D.; Silva, J.E. & Costa, U.F. (1982): Calcium deficiency in clayey B Horizons of savanna Oxisols.- Soil Science, 133: 378-382.

Robertson, I.; Ford, J.A.; McIntosh, W.-B. & Dunnigan, G. (1980): The role of cereals in the aetiology of nutritional rickets: the lesson of the Irish Nutritional Survey 1943-8.- British Journal of Nutrition, 45: 17-22.

Rodriguez, M.; Felsenfeld, A.J. & Llach, F. (1990): Aluminium administration in the rat separately affects the osteoblast and bone mineralization.- Journal of Bone and Mineral Research, 5: 59-67.

Rombo, G.O. (2010): Rickets in Rift Valley.- http://www.ku.ac.ke/images/stories/docs/publications/enviromental_human/rickets_in_R_Valley.pdf [2010/11/12].

Roquin, C.; Freyssinet, P.; Zeegers, H. & Tardy, Y. (1990): Element-distribution patterns in laterites of southern Mali. Consequences for geochemical prospecting and mineral exploration.- Applied Geochemistry, 5: 303-315.

Ross, A.C.; Manson, J.E.; Abrams, S.A.; Aloia, J.F.; Brannon, P.M.; Clinton, S.K.; Durazo-Arvizu, R.A.; Gallagher, J.C.; Gallo, R.L.; Jones, G.; Kovacs, C.S.; Mayne, S.T.; Rosen, C.J. & Shapses, S.A. (2011): The 2011 dietary reference intakes for calcium and vitamin D: What dietetics practitioners need to know.- Journal of the American Dietetic Association, 111: 524-527.

Sanchez, P.A. & Buol, S.W. (1975): Soils of the tropics and the world food crisis.- Science, 188: 598-603.

Sanginga, N.; Okogun, J.A.; Akobundu, I.O. & Kang, B.T. (1995): Phosphorus requirement and nodulation of herbaceous and shrub legumes in low P soils of a Guinean savanna in Nigeria.- Applied Soil Ecology, 3: 247-255.

Sann, I.L.; David, L.; Galy, G. & Romand-Monier, M. (1978): Copper deficiency and hypocalcaemic rickets in a small-for-date infant.- Acta Paediatrica, 67: 303-307.

Sasaki, S.; Iwata, H.; Ishiguron, N.; Habuchi, O. & Miura, T. (1994): Low-selenium diet, bone and articular-cartilage in rats.- Nutrition, 10: 538-543.

Scheffer, F. & Schachtschabel, P. (2002): Lehrbuch der Bodenkunde.- 15. ed.; 593 pp.; Heidelberg.

Schlemmer, U. (2010): Eine einfache und spezifische Methode zur Bestimmung der Phytinsäure und anderer Inositolphosphate in Lebens- und Futtermitteln.- VDLUFA Schriftenreihe, 66: 698-705.

Schlemmer, U.; Frolich, W.; Prieto, R.M. & Grases, F. (2009): Phytate in foods and significance for humans: food sources, intake, processing, bioavailability, protective role and analysis.- Molecular Nutrition and Food Research, 53: S330-S375.

Schlemmer, U.; Jany, K.-D.; Berk, A.; Schulz, E. & Rechkemmer, G. (2001): Degradation of phytate in the gut of pigs. Pathway of gastrointestinal inositol phosphate hydrolysis and enzymes involved.- Archives of Animal Nutrition, 55: 255-280.

Schlüter, T. (2006): Geological atlas of Africa. with notes in stratigraphy, tectonics, economic geology, geohazards and geosites of each country.- 1. ed.; 308 pp.; Berlin.

Schüller, H. (1979): Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden.- Zeitschrift für Pflanzenernährung und Bodenkunde, 123: 48-63.

Schulin, R.; Johnson, A. & Frossard, E. (2010): Trace element deficient soils.- In: Hooda, P. [Ed.]: Trace elements in soils: 175-197; Chichester.

Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.] (2013): Essentials of medical geology. Impacts of the natural environment on public health.- 2. ed.; 805 pp.; Amsterdam.

Selinus, O. (2004): Medical geology. An emerging speciality.- Terrae, 1: 8-15.

Semmel, A. (1993): Grundzüge der Bodengeographie.- 3. ed.; 127 pp.; Stuttgart.

Sharp, C.A.; Oginni, L.M.; Worsfold, M.; Oyelami, O.A.; Risteli, L.; Risteli, J. & Davie, M.W.J. (1997): Elevated collagen turnover in Nigerian children with calcium-deficiency rickets.- Calcified Tissue International, 61: 87-94.

Shitumbanuma, V.; Tembo, F.; Tembo, J.M.; Chilala, S. & Ranst, E.V. (2007): Dental fluorosis associated with drinking water from hot springs in Choma District in southern province, Zambia.- Environmental Geochemistry and Health, 29: 51-58.

Shomar, B.; Müller, G.; Yahya, A.; Askar, S. & Sansur, R. (2004): Fluorides in groundwater, soil and infused black tea and the occurrence of dental fluorosis among school children of the Gaza Strip.- Journal of Water and Health, 2: 23-35.

Shorter, J.P.; Massawe, J.; Parry, N. & Walker, R.W. (2010): Comparison of two village primary schools in northern Tanzania affected by fluorosis.- International Health, 2: 269-274.

Sierra, O.L.; Alarcon, Y.; Penaloza, L.N.; Abrams, S.A.; Zerwekh, J.E. & Novoa, F. (2000): Fractional intestinal calcium absorption in children with rickets and controls from Cauca, Colombia.- Journal of Bone Mineral Research, 15: S357.

Sillanpää, M. & Jansson, H. (1992): Status of cadmium, lead, cobalt and selenium in soils and plants of thirty countries.- 1. ed.; 195 pp.; Rome.

Sillanpää, M. (1982): Micronutrients and the nutrient status of soils. A global study.- 48. FAO Soils Bulletin; 444 pp.; Rome.

Skinner, H.C.W. (2013): Mineralogy of bones.- In: Selinus, O.; Alloway, B.; Centeno, J.A.; Finkelman, R.B.; Fuge, R.; Lindh, U. & Smedley, P. [Eds.]: Essentials of medical geology. Impacts of the natural environment on public health: 665-688; Amsterdam.

Skoglund, E.; Carlsson, N.G., & Sandberg, A.S. (1997): Determination of isomers of inositol mono- to hexaphosphates in selected foods and intestinal contents using high-performance ion chromatography.- Journal of Agriculture and Food Chemistry, 45: 431-436.

Sly, M.R.; Walt, van der W.H.; Bruyin, du D.B.; Pettifor, J.M. & Marie, P.J. (1984): Exacerbation of rickets and osteomalacia by maize: a study of bone histomorphometry and composition in young baboons.- Calcified Tissue International, 36: 370-379.

Smedley, P.L.; Edmunds, W.M.; West, J.M.; Gardner, S.J. & Pelig-Ba, K.B. (1995): Vulnerability of shallow groundwater quality due to natural geochemical environment. Health problems related to groundwater in the Obuasi and Bolgatanga areas, Ghana.- 1. ed.; 122 pp.; Keyworth.

Smith, B.; Breward, N.; Crawford, M.B.; Galimaka, D.; Mushiri, S.M. & Reeder, S. (1996): The environmental geochemistry of aluminium in tropical terrains and its implications to health.- In: Appleton, J.D. [Ed.]: Environmental geochemistry and health. With special reference in developing countries: 141-152; London.

Smith, B.J. (1981): Slope evolution in the Gwari Hills, Kaduna State, Nigeria.- Singapore Journal of Tropical Geography, 2: 57-67.

Sonibare, J.A.; Akeredolu, F.A.; Obanijesu, E.O. & Adebiyi, F.M. (2007): Contribution of volatile organic compounds to Nigeria's air shed by petroleum refineries.- Petroleum Science and Technology, 25: 503-516.

Sonneveld, B.G.J.S. (1996): Soil map of Nigeria; 1:1300000; Wageningen.

Stacey, S.P.; McLaughlin, M.J. & Hettiarachchi, G.M. (2010): Fertilizer-borne trace element contaminants in soils.- In: Hooda, P. [Ed.]: Trace elements in soils: 135-153: West Sussex.

Stadlmayr, B.; Charrondiere, U.R.; Enujiugha, V.N.; Bayili, R.G.; Fagbohoun, E.G.; Samb, B.; Addy, P.; Barikmo, I.; Ouattara, F.; Oshaug, A.; Akinyele, I.; Annor, G.A.; Bomfeh, K.; Ene-Obong, H.; Smith, I.F.; Thiam, I. & Burlingame, B. (2012): West African Food Composition Table.- 1. ed.; 145 pp.; Rome.

Staessen, J.A.; Roels, H.A.; Emelianov, D.; Kutznetsova, T.; Thijs, L.; Vangronsveld, J. & Fagard, R. (1999): Environmental exposure to cadmium, forearm bone density and risk of fractures: a prospective population study.- Lancet, 353: 1140–1144.

Steffens, D. (2004): Agrikulturchemisches Praktikum.- 1. ed.; 137 pp.; Stuttgart.

Steinnes, E. (2011): Soil and human health.- In: Sauer, T.J.; Norman, J.M. & Sivakumar, M. [Eds.]: Sustaining soil productivity in response to global climate change. Sciences, politics and ethics: 54-63; Chichester.

Steinnes, E. (2009): Soils and geomedicine.- Environmental Geochemistry and Health, 31: 523-535.

Storey, E. (1961): Strontium rickets: Bone, calcium and strontium changes.- Australasian Annals of Medicine, 10: 213-222.

Svensson, O.; Reinholt, F.P. & Engfeldt, B. (1987): The parathyroid gland in metal rickets.- Acta Pathologica et Microbiologica Scandinavica, 95: 309-314.

Tagwira, F.; Piha, M. & Mugwira, L. (1993): Zinc distribution in Zimbabwean soils and its relationship with other soil factors.- Communications in Soil Science and Plant Analysis, 24: 841-861.

Tan, J.; Zhu, W.; Wang, W.; Li, R.; Hou, S.; Wang, D. & Yang, L. (2002): Selenium in soil and endemic diseases in China.- The Science of the Total Environment, 284: 227-235.

Tan, J. [Ed.] (1989): The atlas of endemic diseases and their environments in the people's Republic of China.- 1. ed.; 194 pp.; Beijing.

Tardy, Y. (1997): Petrology of laterites and tropical soils.- 1. ed.; 408 pp.; Rotterdam.

Tardy, Y. & Nahon, D. (1985): Geochemistry of laterites, stability of Al-goethite, Al-hematite and Fe3+-kaolinite in bauxites and ferricretes: an approach to the mechanism of concretion formation.- American Journal of Science, 285: 865-903.

Tekin, E.; Varol, B. & Friedman, G.M. (2001): A preliminary study: celestite-bearing gypsum in the Tertiary Sivas basin, central-eastern Turkey.- Carbonates and Evaporites, 16: 93-101.

Teotia, S.P.S. & Teotia, M. (2008): Authors response.- Indian Journal of Medical Research, 129: 674-675.

Teotia, M.; Teotia, S.P.S. & Sing, K.P. (1998): Endemic chronic fluoride toxicity and dietary calcium-deficiency interaction syndromes of metabolic bone disease and deformities in India: Year 2000.- Indian Journal of Pediatrics; 65: 371-381.

Thacher, T.D.; Fischer, P.R.; Tebben, P.J.; Singh, R.J.; Cha, S.S.; Maxson, J.A. & Yawn, B.P. (2013): Increasing incidence of nutritional rickets. A population-based study in Olmsted County, Minnesota.- Mayo Clinic Proceedings, 88: 176-183.

Thacher, T.D.; Aliu, O.; Griffin, I.; Pam, S.; O'Brien, K.; Imade, G. & Abrams, S. (2009): Meals and dephytinization affect calcium and zinc absorption in Nigerian children with rickets.- The Journal of Nutrition, 139: 926-932.

Thacher, T.D.; Fischer, T.D.; Strand, P.R. & Pettifor, J.M. (2006): Nutritional rickets around the world.- Annuals of Tropical Paediatrics, 26: 1-16.

Thacher, T.D (2003): Calcium-deficiency rickets.- In: Hochberg, Z. [Ed.]: Vitamin D and rickets: 105-125; Basel.

Thacher, T.D.; Fischer, P.R. & Pettifor, J.M. (2002): The usefulness of clinical features to identify active rickets.- Annals of Tropical Paediatrics, 22: 229-237.

Thacher, T.D.; Fischer, P.R.; Pettifor, J.M.; Lawson, J.O.; Isichei, J.O. & Chan, G.M. (2000): Case control study of factors associated with nutritional rickets in Nigerian children.- Journal of Pediatrics, 137: 367-373.

Thacher, T.D.; Fischer, P.R.; Pettifor, J.M.; Lawson, J.O.; Isichei, C.O.; Reading, J.C. & Chan, G.M. (1999): A comparison of calcium, vitamin D or both for nutritional rickets in Nigerian children.- The New England Journal of

Medicine, 341: 563-568.

Thornton, I. & Giglioli, M.E.C. (1965): The mangrove swamps of Keneba, lower Gambia river basin, II. Sulphur and pH in the profiles of swamp soils.- Journal of Applied Ecology, 2: 257-269.

Tijani, M.N.; Okunlola, O.A. & Abimbola, A.F. (2006): Lithogenic concentrations of trace metals in soils and saprolites over crystalline basement rocks: a case study from SW Nigeria.- Journal of African Earth Sciences, 46: 427-438.

Trescases, J.J. (1992): Chemical weathering.- In: Butt, C.R.M. & Zeegers, H. [Eds.]: Regolith exploration geochemistry in tropical and subtropical terrains. Handbook of exploration geochemistry: 25-40; Amsterdam.

Turaki, Z.K. (2007): Determination of calcium and phosphorus in staple foods in rickets prevalent areas in Kaduna State.- 76 pp.; Ahmadu Bello University Zaria, Nigeria [Master thesis].

Turner, D.P. (2000): Soils of Kwazulu-Natal and Mpumalanga: recognition of natural soil bodies.- 265 pp.; University of Pretoria, South Africa [Doctoral thesis].

Udo, E.J. & Fagbami, A. (1979): The profile distribution of total and extractable Zn in selected Nigerian soils.- Communications in Soil Science and Plant Analysis, 1: 1141-1161.

UNICEF (2011): Bangladesh national drinking water survey of 2009.- 1. ed.; 192 pp.; Dhaka.

Valette, J. & Ibanga, I.J. (1984): The detailed survey of the experimental farm of the Institute for Agricultural Research, Samaru, Zaria, Nigeria.- 1. ed.; 64 pp.; Zaria.

VanderJagt, D.J.; Morales, M; Thacher, T.D.; Diaz, M. & Glew, R.H. (2001): Bioelectrical impedance analysis of the body composition of Nigerian children with calcium-deficiency rickets.- Journal of Tropical Paediatrics, 47: 92-97.

Vanlauwe, B.; Diels, J.; Lyasse, O.; Aihou, K.; Iwuafor, E.; Sangina, N.; Merckx, R. & Deckers, J. (2002): Fertility status of soils of the derived savanna and northern guinea savanna and response to major plant nutrients, as influenced by soil type and land use management.- Nutrient Cycling in Agroecosystems, 62: 139-150.

Wake, H. (2004): Oil refineries. A review of their ecological impacts on the aquatic environment.- Estuarine, Coastal and Shelf Science, 62: 131-140.

Walker, R.W.; Masuki, G.; Kinabo, G. & McLarty, D.G. (1996): Calcium-deficiency rickets in rural Tanzania: is part of the answer in the water?- Transactions of the Royal Society of Tropical Medicine and Hygiene, 90: 479.

Wall, J.R.D [Ed.] (1979): Land resource of central Nigeria. Agricultural development possibilities. Kaduna Plains.- Vol. 5B; 130 pp.; Surrey.

Walter, E.A.; Scariano, J.K.; Easington, C.R.; Polaco, A.M.; Hollis, B.W.; Dasgupta, A.; Ram, S. & Glew, R.H. (1997): Rickets and protein malnutrition in northern Nigeria.- Journal of Tropical Pediatrics, 43: 98-102.

Walton, K.C. (1988): Environmental fluoride and fluorosis in mammals.- Mammal Review, 18: 77-90.

Wang, C.; Brown, S. & Bhattacharyya, M.H. (1994): Effect of cadmium on bone calcium and 45Ca in mouse dams on a calcium-deficient diet. Evidence of Itai-Itai like syndrome.- Toxicology and Applied Pharmacology, 127: 320-330.

Wang, Z. & Gao, Y. (2001): Biochemical cycling of selenium in Chinese environments.- Applied Geochemistry, 16: 1345-1351.

Watson, P.E. & McDonald, B.W. (2007): Seasonal variation of nutrient intake in pregnancy. Effects on infant measures and possible influence on diseases related to season of birth.- European Journal of Clinical Nutrition, 61: 1271-1280.

Watts, M.J.; O'Reilly, J.; Maricelli, A.; Coleman, A.; Ander, E.L. & Ward, N.I. (2010): A snapshot of environmental iodine and selenium in La Pampa and San Juan provinces of Argentina.- Journal of Geochemical Exploration, 107: 87-93.

Webb, J.L.A. (1992): Ecological and economic change along the middle reaches of the Gambia River, 1945-1985.- African Affairs, 91: 543-65.

Weil, P. (1986): Agricultural intensification and fertility in The Gambia.- In: Penn, W. [Ed.]: Culture and reproduction: an anthropological critique of demographic transition theory: 294-320; Boulder.

Weischet, W. (1980): Die ökologische Benachteiligung der Tropen.- 2. ed.; 127 pp.; Stuttgart.

Welch, R.M. (2002): The impact of mineral nutrients in food crops on global human health.- Plant and Soil, 247: 83-90.

Welch, R.M.; Meisner, C.A.; Hassan, N.; Duxbury, J.M.; Rutzke, M.; Fischer, P.R.; Rahman, A.; Cimma, J.P.; Kyaw-Myrint, T.O.; Kabir, A.L.; Talukder, K.; Staab, D.B.; Haque, S. & Combs, G.F. (1998): Mineral status in relation to rickets in Chakaria, Bangladesh.- https://centre.icddrb.

org/images/jddr161_phn-mineral-status.pdf [2012/8/29].

Wharton, B. & Bishop, N. (2003): Rickets.- The Lancet, 362: 1389-1400.

Whitehead, D.C. (2000): Nutrient elements in grasslands. Soil-plant-animal relationships.- 1. ed.; 363 pp.; Oxon.

Wills, M.R.; Phillips, J.B.; Day, R.C. & Bateman, E.C. (1972): Phytic acid and nutritional rickets in immigrants.- The Lancet, 299: 771-773.

WHO (2011): Guidelines for drinking-water quality.- 4. ed.; 541 pp.; Geneva.

WHO (2009): Calcium and magnesium in drinking water. Public health significance.- 1. ed.; 180 pp.; Geneva.

WHO (2006): WHO Child Growth Standards. Length/height-for-age, weight-for-age, weight-for-length, weight-for-height and body mass index-for-age. Methods and development.- 1. ed.; 312 pp.; Geneva.

Wilke, B.W.; Duke, B.J. & Jimoh, W.L.O. (1991): Mineralogy and chemistry of harmattan dust in northern Nigeria.- Catena, 11: 91-96.

Williams, C.D. (1946): Rickets in Singapore.- Archives of Disease in Childhood, 21: 37-51.

Wright, N.J.; Thacher, T.D.; Pfitzner, M.A. & Pettifor, J.M. (2005): Causes of lead toxicity in a Nigerian city.- Archives of diseases in children, 90: 262-266.

Xie, Z.M.; Ye, Z.H. & Wong, M.H. (2001): distribution characteristics of fluoride and aluminium in soil profiles of an abandoned tea plantation and their uptake by six woody species.- Environmental International, 26: 341-346.

Yabe, J.; Ishizuka, M. & Umemura, T. (2010): Current levels of heavy metal pollution in Africa.- Journal of Veterinary Medical Science, 72: 1257-1263.

Yang, X.-E.; Chen, W.-R. & Feng, Y. (2007): Improving human micronutrient nutrition through biofortification in the soil-plant system: China as a case study.- Environmental Geochemistry and Health, 29: 413-428.

Young, A. (1976): Tropical soils and soil survey.- 1. ed.; 468 pp.; Cambridge.

Zhang, B.; Yang, L.; Wang, W.; Li, Y. & Li, H. (2011): Environmental selenium in the Kashin-Beck-disease area, Tibetan Plateau, China.- Environmental Geochemistry and Health, 33: 495-501.

Zheng, Y.; Geen, van A.; Stute, M.; Dhar, R.; Mo, Z.; Cheng, Z.; Horneman, A.; Gavrieli, I.; Simpson, H.J.; Versteeg, R.; Steckler, M.; Grazioli-Venier, A.; Goodbred, S.; Shahnewaz, M.; Shamsudduha, M.; Hoque, M.A. & Ahmed, K.M. (2005): Geochemical and hydrogeological contrasts between shallow and deeper aquifers in two villages of Araihazar, Bangladesh: implications for deeper aquifers as drinking water sources.- Geochimica et Cosmochimica Acta, 69: 5203-5218.

Zeese, R.; Schertmann, U.; Tietz, G.F. & Jux, U. (1994): Mineralogy and stratigraphy of three deep lateritic profiles in the Jos Plateau (Central Nigeria).- Catena, 21: 195-214.

Zessa, A. & Tasciotti, L. (2010): Urban agriculture, poverty and food security. Empirical evidence from a sample of developing countries.- Food Policy, 35: 265-273.

Zinßer, I. (unpublished, 2012): Polymorphisms of the vitamin D receptor gene and the 24-hydroxylase enzyme in Nigerian children with rickets.- 155 pp.; Julius-Maximilians-Universität Würzburg, Germany [Doctoral thesis].