Environmental Transfer of Radionuclides in a Sub-Saharan Africa Setting

PhD Thesis

By

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DEDICATION

I dedicate this PhD Research to my mother**, Mrs Comfort E. Doroh**

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LIST OF ACRONYMS

BAF	Bioaccumulation factor
Bq/kg or mg/kg	Becquerel per kilogram or milligrams per kilogram
BSAF	Biota sediment accumulation factor
BWG	Biota Working Group
CEC	Cation Exchange Capacity
CF	Concentration factor
CCV	Continuous Calibration Verification
CRs OR TF	Concentration Ratios/ Transfer Factor
DCC	Dose Conversion Coefficient
EMCL	Environmental Media Concentration Limit
EMRAS	Environmental Modelling for Radiation Safety
ERICA	Environmental Risk from Ionising Contaminants: Assessment and Management
FAO	Food and Agricultural Organisation
FES	Frayed edge sites
GERITU	Geregu and Itu sample data
GM	Geometric Mean
GSD	Geometric Standard Deviation
IAEA	International Atomic Energy Agency
ICPOES	Inductively Coupled Plasma Optical Emission Spectroscopy
ICRP	International Commission of Radiological Protection
IUR	International Union of Radiologists
K_{dl}/K_{Dl}	Solid to liquid Distribution Coefficient
MAC	Media Activity Concentration
MAE	Mean Absolute Error
MODARIA	Modelling and Data for Radiological Impact Assessment
MP-AES	Microwave Plasma Atomic Emission Spectrometer
NAEC	Nigeria Atomic Energy Commission
NPP	Nuclear Power Plant
NS	Nash and Sutcliffe
OM	Organic Matter
PSS	Prediction Sum of Square
QA/QC	Quality Assurance/ Quality Control
RAPs	Reference Animals and Plants
RCs	Radiocaesium
RIP	Radiocaesium Interception Potential
RQ	Risk Quotient
SSAD/SSA	Sub-Saharan Africa Database/ Sub-Saharan Africa
SPSS	Statistical Package for Social Science
UNESCO	United Nation Educational Scientific Cultural Organisation
USDOE	United State Department of Energy
WHO	World Health Organisation
WTD	Wildlife Transfer Database

ABSTRACT

In the last two decades, interest in the development of nuclear programmes in Sub-Saharan Africa (SSA) has increased. To ensure that the potential human and environmental ionising radiation exposure from nuclear developments within SSA can be adequately assessed, knowledge of radionuclide transfer within SSA ecosystems is required. Most of the research undertaken to date on radionuclide transfer to humans and wildlife has focused on studies within Europe and North America. These studies have provided data which form the basis of the generic transfer parameters used within the international system of radiological protection. Given that agricultural practices, diet, soils, food crops, wildlife and climatic conditions in SSA are very different to those in Europe and North America, the present study focuses on environmental radionuclides transfer in SSA and evaluates the extent to which the current generic transfer parameters derived from international data compilations are applicable in a SSA setting.

A systematic review of literature on radionuclide and stable element concentrations in SSA species (wildlife and agricultural food crops) and associated environmental media (soil, water, sediment) was conducted. Elemental concentration data were compiled for marine, freshwater and terrestrial ecosystems and these data were used to derive transfer parameter values that were reported within the Sub-Saharan Africa Database (SSAD) of transfer parameters.

A review of the SSAD data highlighted a lack of transfer parameter values for various radionuclide-organism combinations. Therefore, a sampling campaign was undertaken at two case study locations in SSA to help to address some of the SSAD data gaps. The case study locations were Geregu in Kogi State and Itu in Akwa-Ibom state, both are proposed locations for nuclear power plant construction in Nigeria. The sampling campaign involved the collection of soil, agricultural food crops, and wildlife samples. Animal sampling focused on the Reference Animals & Plants (RAPs) defined by the International Commission on Radiological Protection and was conducted in accordance with Schedule 1 of the Home Office guidelines for animal use in research. Agricultural food crops and wildlife samples were prepared and analysed to determine the concentration of stable elements using Microwave Plasma Atomic Emission Spectrometry (MP-AES); transfer for a given stable element was assumed to be representative of the transfer of radioisotopes of that element. Dose assessment was undertaken using site specific

concentrations obtained from the case study location to determine the potential environmental impact of the planned nuclear power plant in Nigeria. To facilitate emergency preparedness planning for the planned nuclear power plant in an SSA setting, a study on Radiocaesium Interception Potential (RIP) of the principal soil types in Nigeria was undertaken. The resultant RIP data were used to test the applicability of the Absalom (also known as the "SAVE") approach to predicting radiocaesium transfer at two case study locations in Nigeria.

The results of the mean concentration ratios obtained from the database of radionuclide transfer parameter values compiled by the International Atomic Energy Agency (i.e. for non SSA sites (Europe and North America)) and those of the SSAD are different. However, differences in mean concentration ratio values are not consistent in the different wildlife-element combinations. The results of the concentration ratios from the field campaign were comparable to those of the SSAD. For food crops, SSAD transfer parameters were consistently higher than generic transfer parameters obtained from IAEA. The dose assessment results obtained for potential radiation exposure of wildlife using the Environmental Risks from Ionising Contaminants: Assessment & Management (ERICA) Tool and predicted discharges from a planned nuclear power station at Geregu, Nigeria, revealed the risk quotient (RQ) to be less than one and the predicted dose rate was below the screening dose rate of $10\mu Gyh^{-1}$ for each of the organisms considered within the assessment. The RIP measurements for Nigerian soils were low compared to RIP results from other parts of the world. The mean of the measured Cs transfer factor for grass (1.67E-02) growing on nitisol at Geregu was an order of magnitude higher than the Absalom model predicted transfer factor for nitisol (1.66E-03). For Itu, the mean of the measured Cs transfer factor (0.09) for grass growing on gleysol was comparable to the Absalom model predicted transfer factor (0.11) for gleysol. Despite an order of magnitude under-prediction for nitisol, the overall, the Absalom model prediction was good, and this suggests that the model would be applicable to SSA.

A dose assessment undertaken using predicted releases from the reactor type being considered for Nigeria suggested that routine releases were highly unlikely to result in dose rates that exceeded the benchmark value (ERICA screening dose rate equals $10\mu Gyh^{-1}$). This finding provided confidence that the environmental impact of this proposed nuclear development in Nigeria would be negligible from a radiological perspective.

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1. INTRODUCTION

1.1. Introduction

There are different sources of ionising radiation within the environment to which humans and wildlife are being exposed. In the case of humans these include occupational exposure, medical exposure and public exposure situations. For wildlife, the exposure situation includes radiation releases through anthropogenic sources such as mining, oil and gas exploration, industrial activities, releases from nuclear power plants, nuclear weapon testing and other external exposures sources (Pentreath, 2001; ICRP, 2007). There is a long-standing system of radiation protection for humans and the public but, for wildlife, the system of radiation protection started to develop about two decades ago (Copplestone et al., 2001). These systems of radiation protection require an understanding of radiation transfer through the human food chain and in the case of wildlife, it requires an understanding of radiation exposure of representative species (including the International Commission on Radiological Protection Representative Animals and Plants (ICRP RAPs)). Radiation exposure estimation requires knowledge of the transfer of radionuclides through wildlife food chains as well as human food chain.

International and national systems have been developed for demonstrating and ensuring protection of humans and wildlife from the effects of ionising radiation (IAEA, 2006; ICRP, 2007; US DOE, 2003; Copplestone et al., 2001; Howard et al., 2010). Systems developed for wildlife assessment include the ICRP RAPs (ICRP, 2008; ICRP, 2009) and Environmental Risks from Ionising Contaminants; Assessment and Management (ERICA) integrated approach (Brown et al., 2008; Larson et al, 2008; Brown et al., 2016). In the case of the human food chain, the systems include the mechanistic and semi mechanistic approach (Absalom et al., 1999). Approaches developed are required to quantify the transfer of radionuclides to both the human food chain and wildlife. To implement these approaches, there are transfer databases and international handbooks that have been developed to provide parameters, which can be used to calculate internal activity concentration in both humans and wildlife (IAEA, 2010; IAEA, 2014; Copplestone et al., 2013). However, the transfer databases are primarily based on data from Europe and North America (Wood et al., 2013).

There has been little attempt to establish whether data from Europe and North America are applicable for conducting environmental assessment in Sub-Saharan Africa (SSA). Little or no research has demonstrated that reference organisms used in international approaches are well represented in other regions of the world with different climatic conditions and agricultural practices, such as those found in SSA. Research conducted in Australia revealed the need to include reptile among the reference organisms (Hirth et al., 2014), which has now been incorporated into the ERICA integrated approach (Brown et al., 2016). In addition, there are growing numbers of nuclear development programmes in Sub-Saharan Africa (www.world-nuclear-news.org/np-west-africa-states-prepare-mou-o-nuclear-nuclear-cooperation-29071501/html) and as a result, radionuclide releases to the environment are expected to increase and these releases must be assessed. With this understanding, a comprehensive compilation of transfer parameters as well as assessment of radionuclide transfer within the SSA is necessary to ensure that robust radiological risk assessments can be undertaken for SSA.

The applicability of currently developed generic transfer parameters to Sub-Saharan Africa has not been assessed. Some European models (including the 'Absalom' or 'SAVE' approach) applied to Japanese soils after the Fukushima accident over-predicted radiocaesium concentration because it was calibrated for the European soils (Absalom et al.,2001). This might raise questions about the credibility of these models when applied across other different soils and regions. To establish confidence on wider applicability, there is a need to assess model performance against other regions, in this case, SSA.

This PhD research develops, for the first time, a database of transfer parameters for both the human food chain and wildlife for SSA from a range of soil and biota samples. The collection of soil samples across a range of soil types also presented an opportunity to determine radiocaesium transfer as well as establish a spatially implementable model for radiocaesium using the Absalom or (SAVE) model. Applying the 'Absalom' approach to soils from Nigeria enabled the model to be tested against a range of soil types from SSA and further reinforce confidence in its applicability.

Recognising that many agricultural production systems, food products and wildlife species in SSA have few or no data (Twining, 2012), there is a new programme being developed within the International Atomic Energy Agency (IAEA) focusing on the behaviour of radionuclides in arid environments (iaea.org/projects/emras/emras2), such as those found in parts of SSA. Therefore,

the findings of this PhD research programme will have direct international impact as well as being beneficial at both a national (Nigeria) and regional (SSA) level.

1.2. The Sub-Saharan Africa – climatic and geographical distribution

Internationally, concerns are increasing about climate change and the need for transition to cleaner energy sources (Stoett, 2003; Dowdall et al., 2008; Newell and Mulvaney, 2013). In Africa, about 625 million people do not have access to electricity and 730 million people use potentially hazardous and dirty fuel for cooking (Energy Outlook, 2014). There are diverse energy sources in Africa yet the region still faces challenges in meeting its energy requirement (Energy Outlook, 2014) and has recently started to consider other energy sources, such as nuclear power, to boost its energy mix (Eggertson, 2002; Kaggwa and Nhamo, 2013; www.world-nuclear-news.org). Previous analyses have shown that nuclear energy may present an attractive option, especially in countries with high growth projection for energy demand, because of the possibility for greenhouse gas emission reduction (Vaillancourt et al., 2008). Therefore, with increasing interest in nuclear development in SSA, there is hope that the perennial energy challenges of the region would be mitigated, and cleaner energy sources would dominate the region's energy production.

Despite the large population in the Sub-Saharan Africa, the region is also culturally diverse with different ecological systems, history, beliefs, foods and traditions (Munene et al., 2000). The region is located to the south of the Sahara Desert (Figure 1.2) and comprises 48 countries (43 in mainland Africa and 5 islands) (Kreft & Jetz, 2010). The region registered the most rapid demographic growth in the world (2.4 % in 2001 compared to 0.8- 2% other developing regions) (Tabutin et al., 2004).

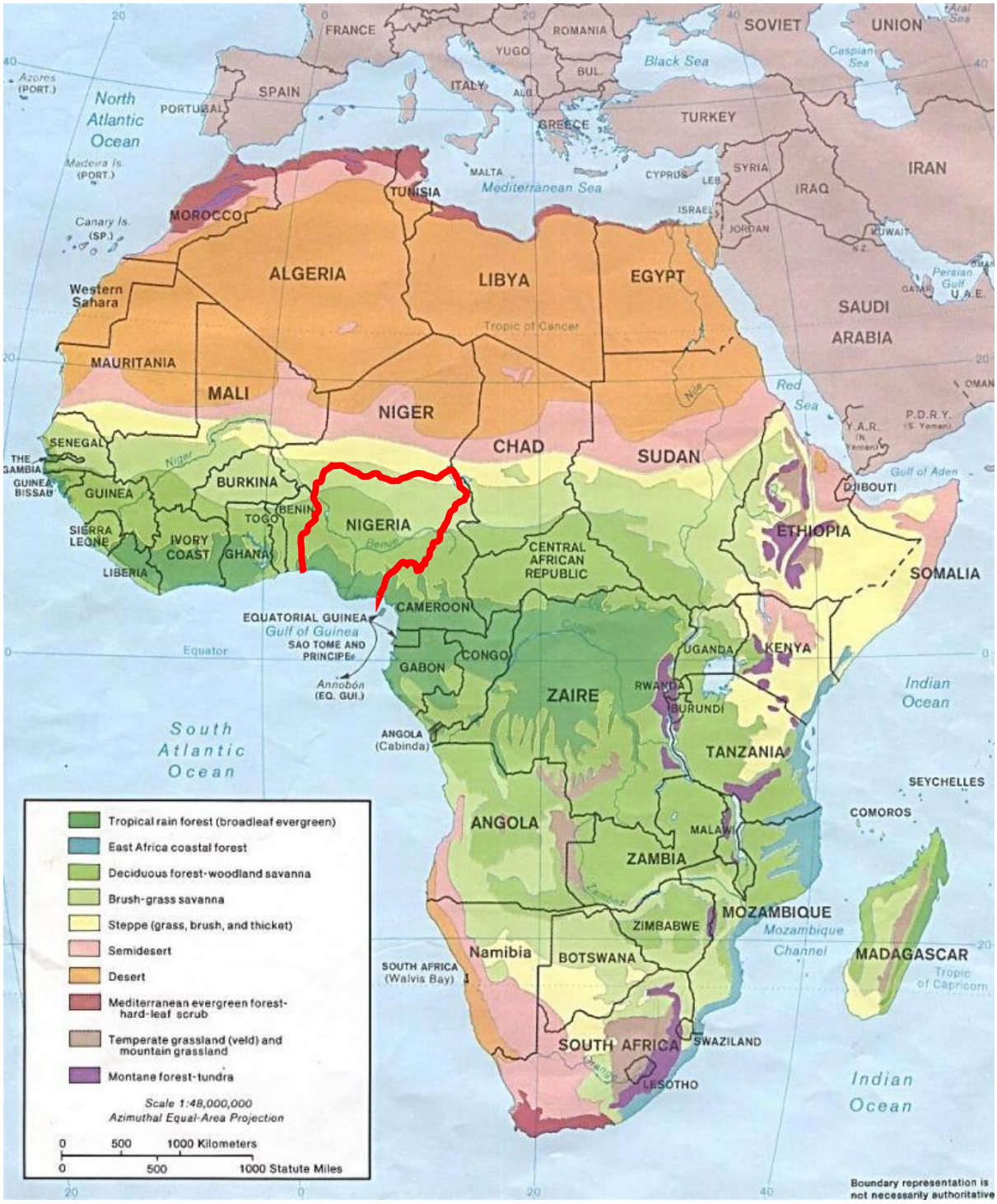

Figure 1.2a. Map of Africa. The large band of desert covering the upper quarter of the African land area is the Sahara Desert. The land area to the south of this is Sub-Saharan Africa (SSA). The land borders of Nigeria, the SSA country used for the field study undertaken as part of this PhD, are marked with a red line. (modified from https://upload.wikimedia.org/wikipedia/commons/c/cd/Africa_Natural_Vegetation.jpg

The impacts of climate change such as rising global average temperature and changes in rainfall affect ecosystems, biodiversity and human systems all over the world (Kotir, 2011). The region has a variety of tropical climatic regimes, including humid, monsoon, arid (desert) and semi-arid (semi-desert) climates (Haile, 2005). Mean annual temperature and rainfall vary between 22-50^{o}C and 600mm-2000mm (Bandyopadhyay et al., 2012). Rainfall pattern is affected by large scale intra-seasonal and interannual climatic variability (Haile, 2005). The region is highly dependent on agriculture and reports have shown that SSA is particularly susceptible to the impact of climate change. (Kotir, 2011).

1.2.1. Distribution of nuclear programmes in SSA

The only SSA country with established nuclear reactors for energy production is South Africa. Other countries (including Nigeria, Ghana, Tanzania, Ethiopia, Angola, Namibia, Mozambique, Rwanda) have small nuclear reactors for scientific research purposes (http://www.world-nuclear-news.org/Articles/Russia-discusses-African-nuclear-power-prospects). However, five countries in SSA (Ghana, Nigeria, Niger, Sudan and Kenya) are considering the introduction of nuclear energy as part of their energy mix (Figure 1.26).

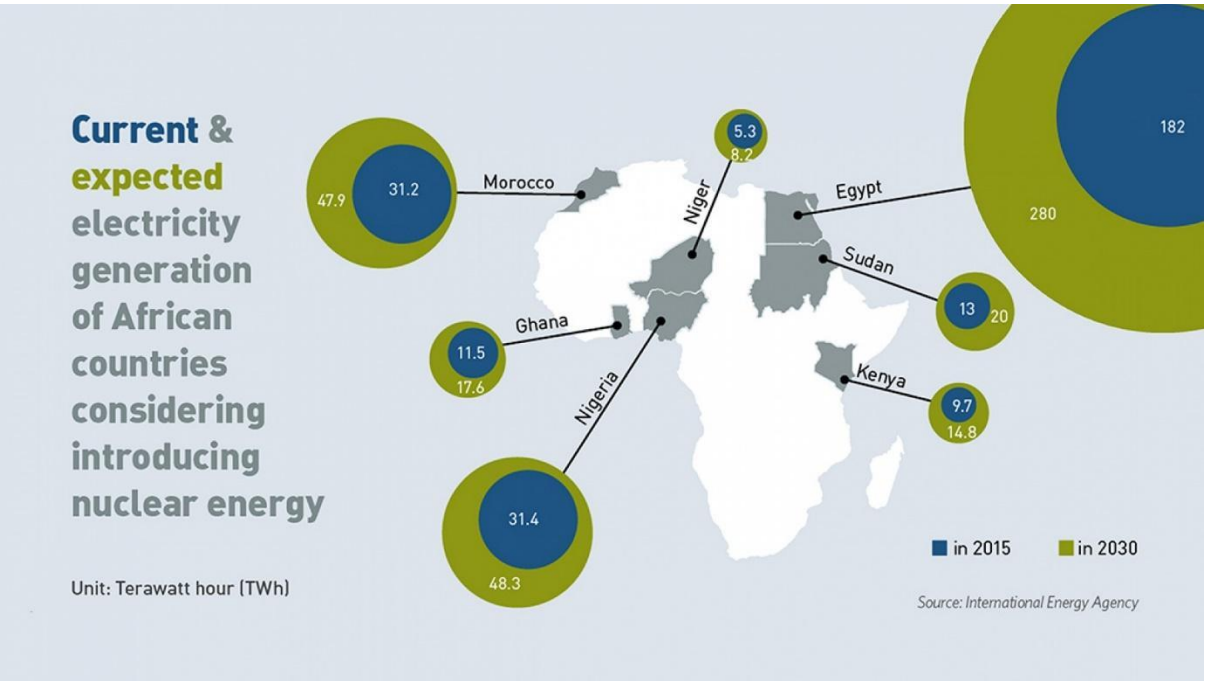

Figure 1.2b. Africa countries with planned and operational nuclear power plants (https://www.iaea.org/newscenter/news/is-africa-ready-for-nuclear-energy)

After feasibility studies, two locations in Nigeria, namely Geregu and Itu, have been proposed for the construction of nuclear power plants. The country is making "notable progress" in strengthening the infrastructure for a new research reactor (VVER-1200 Gen III Nuclear reactor), which is expected to begin operation in 2025 (http://www.world-nuclear-news.org/articles/iaea-helps-nigeria-plan-for-new-research-reactor). For the purpose of radiation protection, it is important to establish a system for the environmental impact assessment of radionuclide releases (Pentreath, 1998; Larsson, 2004; Brown et al., 2008)

1.3. Default assessment organisms

The current wildlife assessment approaches are built on certain parameters including default assessment organisms, transfer parameters, dosimetry and effects (Beresford et al., 2008). The International Commission on Radiological Protection (ICRP), has identified and recommended a set of organisms on which to base the environmental protection of wildlife (ICRP, 2007; ICRP, 2009). Based on this recommendation, research has begun to focus on default assessment organisms (Beresford et al., 2018). These default assessment organisms include the ICRP RAPs (ICRP, 2009) and ERICA reference organisms (Brown et al., 2008)

1.3.1. ICRP Reference Animals and Plants (RAPs)

The International Commission for Radiological Protection (ICRP) has developed a set of 12 Reference Animals and Plants (RAPs) (ICRP,2008, ICRP, 2009). The RAPs are defined for specific taxonomic families (ICRP, 2007; ICRP, 2008; ICRP, 2009; Howard et al., 2013; Beresford et al., 2008a; Vives i Batlle et al., 2010). However, data for the specific family level defined in RAPs can be sparse and sometimes, even when available are very site dependent (Guillén et al., 2018). ICRP RAPs have been recognised internationally to provide guidance on radiological protection all over the world (ICRP, 2009). An ICRP RAP is defined as "*a hypothetical entity with the assumed basic biological features of a particular type of animal or plant, describing generality of a taxonomic level of family, with a well-defined life history, anatomical and physiological properties used for the purpose of relating exposure to dose and dose to effects for that organism*" (ICRP, 2009). Organisms defined in the ICRP RAPs include; Deer, Rat, Duck, Frog, Bee, Earthworm, Crab, Pine tree, Wild grasses, Trout, Flatfish, Seaweed) (ICRP, 2007; ICRP, 2008; ICRP, 2009). The RAPs form the basis for collating and analysing data useful for environmental impact assessment and

to provide advice for humans, wildlife and environmental protection (ICRP, 2008). The RAPs are displayed in brackets in table 1.3a.

Table 1.3a. ERICA Reference Organisms & ICRP Reference Animals and Plants (RAPs) (ICRP,2007; Brown et al., 2016).

Freshwater	Marine	Terrestrial
Amphibian (Frog)	Benthic fish (Flatfish)	Amphibian (Frog)
Benthic Fish	Mollusc- bivalve	Bird (Duck)
Bird (Duck)	Crustacean (Crab)	Detritivores invertebrates
Mollusc- bivalve	Macro algae (Brown seaweed)	Flying insects (Bee)
Crustacean	Mammal	Mollusc- gastropod
Mollusc- gastropod	Pelagic fish	Grasses /herbs (Wild grasses)
Reptile	Phytoplankton	Lichen & Bryophyte
Insect Larvae	Polychaete worm	Mammal- large
Mammals	Reptile	Mammal- small- burrowing (Rat)
Pelagic fish (Salmon/ Trout)	Bird	Reptile
Phytoplankton	Sea anemones/true coral	Shrubs
Vascular plant	Vascular Plant	Annelid (Earthworm)
Zooplankton	Zooplankton	Tree (Pine tree)

The RAPs have been assigned a corresponding dose criterion, the Derived Consideration Reference Levels (DCRLs) (ICRP,2008, Copplestone et al., 2010). The DCRL is a dose rate band within which deleterious effects of ionising radiation on a given RAP may be expected to occur (ICRP, 2008). RAPs are defined at the family level (the most suitable level for generalisation for typical biological traits or features of organisms) and for terrestrial environment, eight RAPs have been considered by ICRP for which studies on radionuclide transfer should be focused. The

families defining the RAPs are widely distributed across the globe (ICRP, 2007). In SSA, some organisms corresponding to the family level defined in the RAPs have been identified, including Muridae- (rat) *Arvicanthis niloticus*, Ranidae-(frog) *Amnirana galamensis*, Apidae- (bee) *Apis mellifera*, Lumbricidae- (earthworm) *Lumbriscus terrestris*, and Poaceae- Wild grass.

Table 1.3b. Terrestrial RAPs and their global distribution (ICRP, 2008)

Terrestrial ICRP RAPs	Specific Family	Distribution of RAPs
Deer	Cervidae	This deer family is well distributed in the Latin America (including Mexico, Central America, South America) (Weber and Gonzalez, 2003)
Rat	Muridae	The Murids are widely distributed in Australia, East Asia and in the SSA and other parts of the world (Murid specie found in SSA include *Arvicanthis niloticus*
Duck	Anatidae	The family Anatidae is distributed across US, Korea, Japan, China, India, New Zealand, Russia, Colombia and Madagascar. It's found in SSA (Oatley and Prys- Jones et al., 1985).
Frog	Ranidae	*Amnirana galamensis* is widely distributed in Africa, SE Asia, S&N Asia, Europe, Australia, Madagascar, N&S America (Penner et al., 2011; Kwapong,2014; Jongsma et al., 2018).
Bee	Apidea	The family Apidea is widely distributed in SSA, Australia, S America, Malaysia, India, Japan, US, Cuba (Rehan et al., 2010).
Earthworm	Lumbricidae	Lumbricidae are widely distributed while they are native to the Paleartic (Europe) They are found in Australia, SSA, Nearctic (Canada & US), Neotropical (S/America &Mexico) (Reynold, 1994, Hendrix et al., 2002)
Pine Tree	Pinaceae	The distribution of pine in the world include N America, Central Europe, Siberia, Japan, Korea, China, Mongolia (McCaughey and Schmidt, 2001, Tombark et al., 2001). There are a few species in SSA
Grass	Poaceae	Poaceae are widely distributed globally. Panicum maximum species are native to Africa and Asia (Aliscioni et al., 2003)

1.3.2. Reference organisms

Environmental Risks from Ionising Contaminants: Assessment and Management' (ERICA) integrated approach also considered, 38 reference organisms, (Beresford, Barnett et al. 2008, Beresford, Gaschak et al. 2008). ERICA defined reference organisms as a series of entities that provide a basis of estimation of radiation dose to a range of organisms, which are typical or representative, of a contaminated environment (Brown, Alfonso et al. 2008).

Both the ICRP and ERICA approaches have been used for conducting environmental radiological assessments in Europe and North America (ICRP, 2007; Larsson, 2008) but relatively few attempts to apply these approaches in other geographical regions (Guillen, Beresford et al. 2018). For Instance, the ICRP RAPs include deer, which is defined at the family level Cervidae, but this family of deer is not present within SSA (Manning et al., 2003; http://www.nhptv.org/wild/cervidae.asp). Similarly, there may be organisms (culturally important and protected species in SSA, which lack data (e.g. Tetradactylus eastwoodae, a species of African reptile) requiring assessment (Branch, 2014), which are not appropriately represented by any of the ERICA reference organisms.

1.4. Aims of the study

The overall aim of this study is to critically evaluate the extent to which current generic transfer parameters that have been developed for assessing radiation impact, which are based largely on data from Europe and North America, are appropriate for undertaking environmental assessments in Sub-Saharan Africa countries with very different ecosystem characteristics. This study focuses on Nigeria as specific case study location, in part, because of proposed new nuclear power construction at Geregu and Itu in Nigeria.

1.5 The study objectives

There are six research objectives to address the research aims which are presented below.

1. To establish a Sub-Saharan Africa Database (SSAD) of radionuclides/ elemental transfer parameters based on systematic review of published and grey sources.
2. To compare SSAD and currently available international transfer parameters primarily developed from Europe and North America data.

3. To characterise elemental transfer of relevant radionuclide analogues at two case study sites in Nigeria
4. To determine stable elements concentration (including these elements Sr, Se, Co, Mo, U, Th, Eu, Ce, Cs) as well as site-specific concentration ratios for wildlife and food crops from the case study location in Nigeria
5. To determine the Radiocaesium Interception Potential (RIP) in the principal Nigerian soils
6. To evaluate the applicability of Absalom's or SAVE approach to major Nigerian soils.

The Figure 1.5 represents a summary of the research aim, objectives and the method adopted to address each of the objectives.

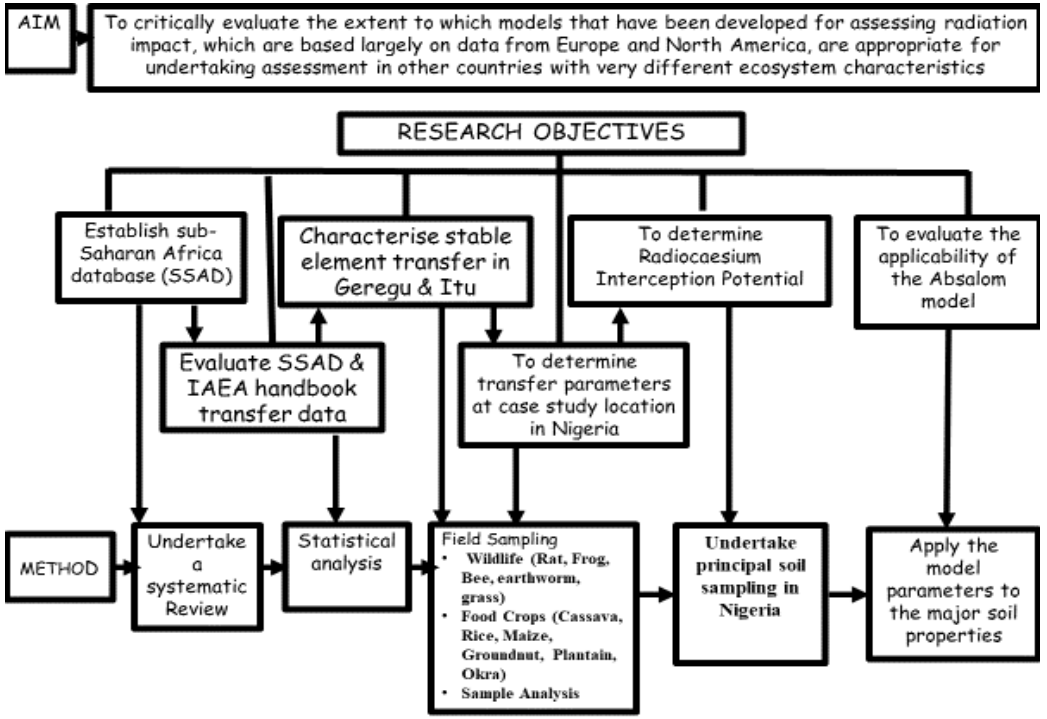

Figure 1.5. Summary of research aim, objectives and methodology.

2.LITERATURE REVIEW

2.1. Introduction

This chapter will establish a conceptual framework of environmental protection, critically review literature on modelling approaches for human food chains and wildlife and highlights the applicability of current radionuclide transfer approaches/models. Furthermore, it will discuss modelling of transfer and the use of Concentration Ratios (CRs) and as well as the Absalom approach. It will evaluate stable elements of relevance and radionuclide analogues and consequently, discuss some factors influencing variation in environmental transfer parameters.

2.2. Sources of radiation

Besides exposure to naturally occurring radionuclides and cosmic radiation, humans and wildlife may be exposed to other anthropogenic radiation sources (Morris, 1988). Accidental discharges from nuclear reactors, medical exposure to X-rays, nuclear weapon testing and some other human activities such as fertilizer application and formulation of animal feed ingredients may release radionuclide contaminants (Olobatoke and Mathuthu, 2015). For example, in Brazil, an experiment revealed an increase of up to 0.87 and 7.6 Bq/kg of natural radionuclide distribution, in grain and green crops respectively when phosphate fertilizer was applied (Saueia and Mazzilli, 2006). Major environmental contaminants from these radiation sources may include strontium, caesium, cobalt, lead, chromium, uranium, iodine, plutonium, and americium isotopes and stable elements. Radiation is the process of emitting energy as waves or particles which may be ionising or non-ionising. Ionisation is the process by which a neutral atom or molecule acquires or losses electric charges (Johansen and Twining, 2010). During operation of nuclear facilities or during a nuclear accident, radionuclide discharges may be released and once released, they may be deposited and accumulate on soil and water bodies where they are absorbed by pastures, food crops, animals and transferred via the human food chain. All radioactive materials are potentially hazardous if absorbed into the body in enough quantity.

2.3. Historical development of radiation protection

Radioactivity was first discovered by Marie Curie in 1903, however, the concept of radiation protection can be traced back to 1925. This is when the term tolerance dose to radiation effects was first used, which was later referred to as deterministic effects or dose limit. Between 1925 and 1945, radiation protection became a science (Kathren and Ziemer, 1980) and bodies such as the International X-ray and Radium Protection Committee was formed which later became the International Commission on Radiological Protection (ICRP). Between 1945-1970, compilations of recommendations made of permissible dose from external radiation sources started to develop and were published in handbooks (including handbook 17) (NCRP,1954). The first report on the effects of radiation by the United Nation Scientific Committee on the effects of Atomic Radiation (UNSCEAR) was published in 1958 and this period also witnessed a lot of nuclear weapon testing. From 1970, the radiation protection concepts gained more recognition, the nuclear regulatory commission began to introduce concept such as "ALARA"- As low as reasonably achievable and the linear non-threshold dose response model was also introduced as basic radiation protection philosophy (Kathren,1996). During this period, the systems of radiation protection were simply based on the justification of practices, optimisation of doses, and limitation of individual risk, developed from the experiences of other learned bodies (such as UNSCEAR & ICRP), concerned with low level radiation risks. The linear non-threshold dose-effect assumption states that every dose has an associated risk of ill-health, all radiation exposure is unsafe, and that radiation has a linear dose response relationship (Kathren, 1996). Peterson (1993) challenged the validity of the linear non-threshold dose-effect assumption and studies by Cohen (1995) on the relationship between environmental radon concentration and lung cancer consistently revealed that linear non-threshold dose-response does not apply in all cases (Kathren, 1996).

2.3.1. Radiation protection ethics and philosophy

In all the developments, the need for radiation assessment and management approaches of the potential impact of radionuclide on human and wildlife was recognised due to attitudes of the public towards radiation and environmental protection (Strand and Oughton, 2002). As a result, existing regulatory practices were re-evaluated and several approaches to regulate both nuclear and non-nuclear sectors were developed. The misuse of nuclear materials, coupled with the challenges of radionuclide waste disposal as well as accidental radionuclide

discharges raised concern on how best to address environmental contaminants and as a result, an overall framework for environmental protection of humans and other living things were developed (Pentreath, 1998; 1999; 2002; 2003a; 2003b). So, radio-ecologists, now consider various philosophies on environmental ethics and moral values (Strand and Oughton, 2002). These philosophical considerations are summarized in figure 2.2a.

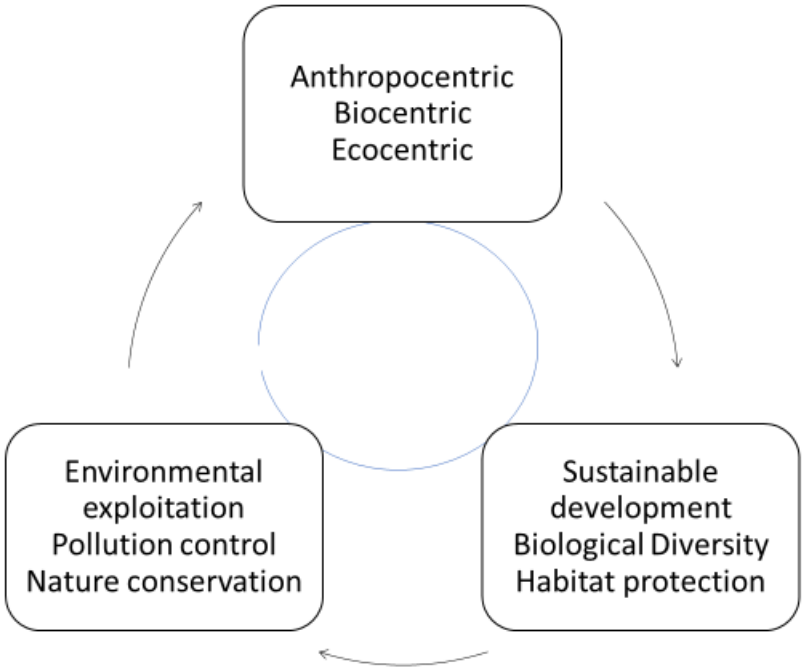

Figure 2.2a. The fundamental philosophy of environmental protection (Pentreath,2004)

The Anthropocentric philosophy views humans as the main or only thing most easily recognised to be of moral standing for environmental protection. However, the biocentric philosophy views moral focus on individual members of a species. It recognises moral obligations to many animal species as they are seen to be feelings (animal rights, welfare and equal and inherent values). In ecocentric philosophy, consideration is about everything in the environment, biotic and abiotic including landscape features (Pentreath, 2004). All the philosophies and ethical views are reflected in a society's, social, cultural and religious perception and approach towards environmental radiation protection (Pentreath, 2004). Nonetheless, in recent years, agreement on broad environmental protection principles has started to emerge. These principles are focused on sustainable development, maintaining biological diversity and habitat protection (Pentreath, 2004). The principles and philosophies are similar and interconnected yet differ in a way that may be helpful to environmental

management or mismanagement. It is interesting that this ethics and philosophical stance would set the context as to what environmental protection is set to achieve (i.e. to ensure protection of man- anthropocentric, individual species biocentric or population- ecocentric) and the why of environmental protection? (for sustainable development, biological diversity and habitat protection) and how to solve challenges of environmental exploitation, pollution control and natural conservation. The approaches to environmental management have recognised the need for exploitation control, pollution control and nature conservation. Controlling these matrices would ensure human activities can progress without interfering with local natural fauna and flora in the environment. Appropriate steps are therefore required to ensure favourable conservation of population of species and if sites are found to be unfavourable, actions need to be taken in line with approaches to environmental management to remedy the situation (Pentreath, 2004).

2.3.2. Development of radiation protection system

The IAEA defines environment "*as the conditions under which humans, animals and plants live/ develop, which sustain life and development especially such condition as affected by human activities*" (IAEA, 2014). The environment needs to be protected from deleterious effects of ionising radiation (IAEA, 2002; ICRP, 2007; Anderson et al., 2009). To protect the environment, international systems capable of ensuring that the environment is adequately protected through assessment and management have been developed (Howard and Larsson, 2008). The overall aim of environmental protection is "*to prevent or reduce the frequency of radiation effects on the biota to a level of negligible impact to the health status of the natural habitats, communities and ecosystems, ensuring environment's biodiversity is maintained and the conservation of species*" (ICRP, 2008). Different regulatory agencies already established to drive policies and regulations on safety, environmental risk assessment and ensure the protection of the environment have been developed (ICRP, 2007; IAEA, 2006). ICRP major scientific challenge was exposure to dose and dose to effect which led to the development of a set of conceptual and numeric models (Pentreath, 2009).

The process of model development resulted to the creation of a Reference man, later, Reference individual (male or female), and thereafter, a Reference person-represented by voxel phantoms (ICRP, 2002). The critical group concept was developed to represent a mean of assessing radiation impact to the public and this was denoted by the "Representative

Person" (Pentreath, 2009). The evolving processes started with the concern for the protection of man. The ICRP issued a statement "*if humans are adequately protected, then other species will also be adequately protected*" (ICRP,2003). However, according to Pentreath. (2009), the protection of man does not ensure or guarantee, the protection of other species in the environment. Eventually, this argument led to the development of ICRP Reference Animals and Plants (ICRP RAPs) (Pentreath, 2009). Management of human radiation exposure has received much attention under different exposure situations (medical, occupational and public exposures) as such managing this risk has evolved the use of the entity referred to as the "*Representative man*". The protective regulatory context was then established upon problem formulation, exposure assessment, dosimetry, effect assessment and risk characterisation (Anderson et al., 2009; Garnier-Laplace et al., 2010; Copplestone et al., 2010). A review of existing environmental assessment approaches/model (USEPA SADA model RESRAD-BIOTA & ERICA tool) model was undertaken as a result of the PROTECT concept (Howard, Beresford et al. 2010). Major variability identified in them was associated with the transfer component of the models (Beresford et al., 2010). Figure 2.2b represents the environmental protection framework.

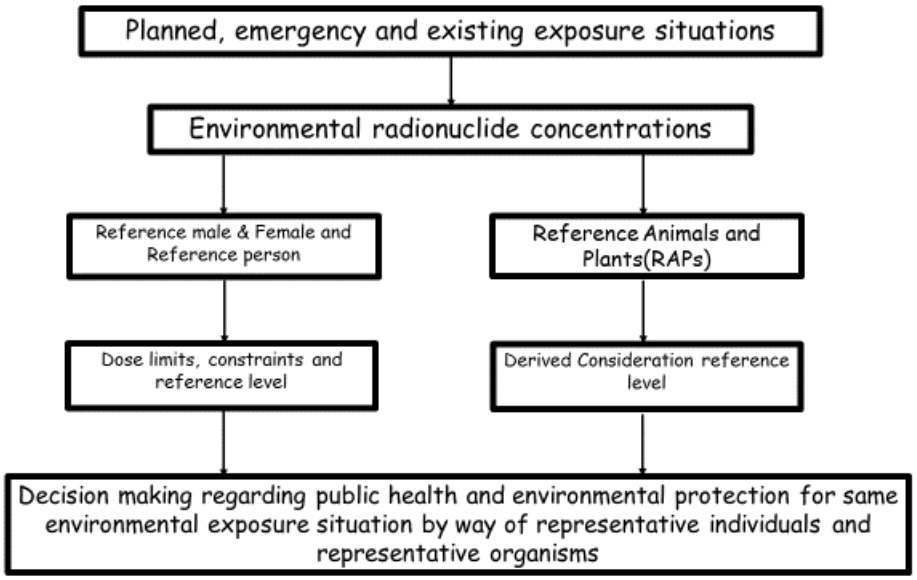

Figure 2.2b. Environmental protection framework (Pentreath, 2005, 2009)

2.4. Radiological assessment approaches/ models

Based on environmental legislation and policy decisions at national or international levels, certain requirements must be followed to assess the environmental impact of ionising radiation (Wood et a., 2009). Environmental assessment approaches and tools have been recommended for addressing these requirements (Beresford et al., 2008a). Models are necessary to stimulate the geometry of external exposure, the bio-kinetics of incorporated radionuclides and the human body (ICRP, 2007) and these models have been established based on a range of experimental investigation and human studies (ICRP, 2007).

There are international systems (including ICRP RAPs and ERICA Integrated approach) (ICRP, 2007, 2008; Beresford et al., 2008; Brown et al., 2008) and national approaches including the United State Department of Energy (US DoE), the England and Wales Environmental Agency which have been developed and used at different levels for conducting environmental assessment (USDoE, 2002; Copplestone et al., 2001; Copplestone et al., 2003). Environmental assessment models or tools are flexible computerised systems that allow users to perform environmental assessment, risk characterisation, record information and decisions and allowing calculations to be performed (Brown et al., 2008). Different approaches have emerged and used to estimate the exposures of wildlife to the effects of ionising radiation (ICRP, 2008; 2009; Howard and Larsson, 2008). However, for human food stuffs, some models which allow environmental assessment of radionuclide transfer to food chain have been developed (including the Absalom or SAVE approach (Absalom et al., 2001)

2.4.1. Food chain approaches

Different approaches have been developed varying from the application of dose limits (Higley et al., 2003) or ecological risk assessment models (Brechignac, 2001), through to frameworks centred on the use of reference fauna and flora (ICRP,2003). Human food chain approaches include RESRAD-BIOTA. This approach has greater functionality and enables prediction of radionuclide transfers using a dynamic allometric (mass dependent) approach (Howard et al., 2010). Available dynamic models are those that have been purpose-built for specific environments (e.g. the marine environment (Vives i Battle et al., 2008; Avila et al., 2004)) and ones that combine elements of human assessment models with parameters from RESRAD-BIOTA & FASSET (Brown et al., 2003) to establish a dynamic transfer model (Howard et al.,

2010). Within the RESTORE project (Restoration strategies for radioactive contaminated ecosystems), which was funded by the European commission, a GIS- based model – Environmental Decision Support System (EDSS) has been developed to model radionuclide transfer from soil through the food chain to humans. EDSS identifies, critical population groups and vulnerable areas based on maps of soil contaminations, soil types, land use and consumption habits (Van der Perk et al., 2000). This model has been applied to Russia, Ukraine, Belarus and contaminated areas in Kazakhstan (Absalom et al., 2001).

2.4.1.1. The Absalom or SAVE approach

This approach describes the uptake of radiocaesium based on soil characteristics (Absalom et al., 2001). Parameter requirements of the approach to determine radiocaesium include labile caesium distribution coefficient (K_D), potassium ion (K^+) concentration in the soil solution (M_k) and soil to plant transfer factor (Absalom et al., 2001). Part of the assumptions of the model include that Cs absorption occurred exclusively on the soil clay fraction and the distribution of the sorbed and solution ^{137}Cs is denoted by a labile distribution coefficient (K_D) estimated as a function of soil clay and exchangeable potassium ion concentration (Absalom et al.,2001). Radiocaesium bioavailability is strongly affected by soil properties such as K^+ and clay content (Smolders et al., 1997). Absalom et al. (1999) presented a model which can be used to predict the activity concentration of radiocaesium in plant for specified soil-caesium contact times utilising readily available soil characteristics (such as % clay, exchangeable K^+ and initial soil radiocaesium content (Absalom et al., 1999). The Absalom approach was applied to the Japanese soil to predict the soil- to- grass transfer of radiocaesium (RCs). Using both measured and predicted RIP and M_k, the model underestimated the transfer values and suggested a recalibration of existing models (Uematsu et al., 2015).

2.4.2. Wildlife approaches

Many approaches and tools have been developed to calculate appropriately exposure of wildlife (non-human biota) to the effects of ionising radiation (Howard et al., 2010). Methodologies used in these models include calculating radionuclide transfer to wildlife, estimation of dose rate to wildlife and risk characterisation (Howard et al., 2010). These approaches include USDOE graded approach (USDoE, 2002), Environmental Agency R&D 128 developed for use in England and Wales (Copplestone et al., 2001; 2003), FASSET (William, 2004), and ERICA (Howard and Larsson, 2008; Brown et al., 2008, 2016). They can be used to

estimate radionuclide transfer to wildlife, estimate dose rates and compare dose rate with some form of criteria to determine risk level. Of these approaches, R&D 128 is the most basic and the only tool which considers noble gases which contribute a major component of the total activity released from many nuclear sites (Howard et al., 2010).

2.4.2.1. ERICA Integrated approach

Environmental Risks from Ionising Contaminants; Assessment and Management (ERICA) was founded between 2004-2007 by the European Union alongside fifteen other organisations in seven European countries (Larsson et al., 2008). The ERICA approach was developed to provide users a guide to assessing the impact of environmental radiation to wildlife as well as ensuring decisions on environmental issues has considered impact to exposures, effects and risks from ionising radiation. Several modelling parameters have been incorporated into the ERICA tool including the transfer database, dose conversion coefficient and radiation effects on non-human biota used specifically for integrating the approach (Brown et al., 2008, 2016). This approach has critically aided decision making related to environmental impact of ionising radiation to non-human biota, assessment and management of exposures, effects and risk (Beresford et al., 2008). ERICA approach defined a series of entities based on the concept of reference organisms (ROs) that are representative of a contaminated environment and which provide the basis of calculating radiation dose rate (Brown et al., 2008, 2016). The ERICA Integrated approach has been applied to the Drigg sand dunes in Cumbria, United Kingdom for which the results indicated no significant impact of ionising radiation on the biota inhabiting the dunes (Wood et al., 2008). The ERICA tool has been applied to a mining site in Asia to assess dose to organisms for screening purposes and to identify the most exposed organisms. The predicted values obtained were two orders of magnitude higher than the measured concentrations of the element (U) from water plants at the site (Oughton et al., 2013). The ERICA Tool has been used in various applications worldwide including environmental impacts from deep geological disposal facilities in the Europe (Smith and Robinson, 2008, 2010; Torudd, 2010; Jaeschke et al., 2013; Posiva, 2014), quantifying environmental impacts from operating and planned nuclear power stations (Nedveckaite et al., 2011; Vanderhove et al., 2013; Li et at., 2015), deployed to formulate radiological quality guidelines for Australian uranium mining sites (Doering and Bollhofer, 2016), scoping analyses in line with newly introduced environmental regulations (Hosseini et al., 2011), Uranium mining impact assessment; assessment of the impact of near surface radioactive waste

repositories in Europe and Australia (Nedveckaite et al., 2013; ANSTO, 2014), assessing release from medical facilities (Carolan et al., 2011), estimating exposures for biota following accidents (Garnier- Laplace et al., 2011; Fuma et al., 2015), inter-comparison and scenario analysis (Beresford et al., 2008a, 2008b, 2010; Yankovich et al., 2010; Vives i battle et al., 2011; Stark et al., 2015). The United Nations Scientific Committee on the effects of Atomic radiation has adopted components of the ERICA to analyse the impact of the 2011 accident at the Fukushima Daichi nuclear power plant (UNSCEAR, 2014; Strand et al., 2014; Vives I battle et al., 2014)

2.5. Radionuclide transfer model application

Model inter-comparison has been undertaken to identify major sources of variability in model performance and capabilities (Beresford et al., 2008). Model application to other different regions have thrown up concerns on wider model applicability. For instance, and according to Uematsu et al. (2015), the application of the Absalom et al approach to the Japanese soils obtained from the vicinity of the Fukushima accident affected area to predict Radiocaesium Interception Potential (RIP) overestimated the RIP values because its initial calibration being meant for the European and not Japanese soil. To obtain reasonable model predictions therefore would depend partly on the quality of data available for the required input parameters (Beresford et al., 2013). Allometric models such as USDOE (2003) have been used successfully to make predictions of radionuclide activity concentration in reptiles and amphibians even when initial design was for homeothermic vertebrates (Wood et al., 2009; Beresford et al., 2010; Yankovich et al., 2010; Beresford and Vives i Battle, 2013; Beresford et al., 2014). Despite variability witnessed in transfer parameter, remarkable improvement in transfer model performance over the years has been observed (IAEA, 2004) and various model predictions were within a factor of three of the observed measurement (IAEA, 2004). Several approaches including the IAEA SRS-19 coastal dispersion model as incorporated into the ERICA model (IAEA, 2001; Brown et al., 2008) have been used to generate sorts of input data for wildlife assessment. The ERICA integrated approach (Larsson et al.,2008) and ERICA Tool as described by Brown et al. (2008) has been used for the assessment of transfer of radionuclide to wildlife (Yankovich et al., 2010). In Nigeria, the ERICA approach has been applied to assess the radiological impact of the proposed nuclear power plant (NPP) on human and non-human biota (Aliyu et al., 2015). However, applying European model to the

SSA may raise some concerns especially when the appropriateness of such model has not been confirmed.

2.6. Transfer modelling and the use of Concentration Ratios (CR)

Many of the currently existing environmental impact assessment models conformed to a generic structure of using radionuclide activity concentration data in environmental media as modelling input (Vives I Battle et al., 2007; Beresford et al., 2008; Beresford et al., 2019). In the modelling of transfer, the media activity concentration is used to estimate the internal and external dose rate for each organism, and these are compared with radiation effects data to determine if the organism is adequately protected (Wood et al., 2008). The transfer of radionuclides to wildlife is generally represented by simple Concentration Ratios (CRs), which allow prediction of whole organism activity concentrations from activity concentrations in environmental media (soil, water or air) (Beresford et al ., 2008a; 2008b; 2008c; Copplestone et al., 2001; Hosseini et al., 2008; USDOE, 2003; Hosseini et al., 2008; Beresford et al ., 2019). Most common approaches estimate transfer to wildlife in assessment models using concentration ratio (Beresford et al., 2016) and CR is defined by the equation below

$$CR_{wo\text{-}soil} = \frac{\text{Activity concentration of in biota whole organism (Bqkg}-1 \text{ fresh mass)}}{\text{Activity concentration of in soil (Bqkg}-1 \text{ dry mass)}}$$

In 1965, Ward et al. (1965), first measured the transfer of radionuclides (Radiocaesium) to animal derived food products (Howard et al., 2009) and referred to it as transfer coefficient. Consequently, concentration ratio was developed as an alternative method to quantify transfer from media to biota. Concentration ratio is simply the equilibrium ratio of the radionuclide activity concentration in the biota (fresh mass) to the radionuclide activity concentration in the media (soil, sediment, water, air) (Hosseini et al., 2008; Howard et al., 2009). Using this approach to quantify transfer has the following merits;

1) It is simple, coherent and user friendly.
2) Relatively available large CRs data for organisms, elements, ecosystems compared to other methods.
3) It is consistent with the method used to derive parameter values in existing models (Hosseini et al., 2008; Beresford et al., 2008).

4) The CRs approach can be used in both human food chain and non-human biota radionuclide environmental impact assessment.

However, it has been limited by the assumption of equilibrium between two environmental compartments and may not be suitable for a situation of accidental occurrences (Howard et al., 2013). Again, CR values can be highly variable due to site specific factors (including soil properties and water chemistry) (IAEA, 2009; Avila et al., 2004; Vives i battle et al., 2010; Beresford, 2010; Higley et al., 2010; Beresford et al., 2016; Beresford and Willey, 2019). For wildlife, prediction by different models often vary by the 2-5 order of magnitude for same assessment (Beresford and Willey, 2019). Assessing exposure of wildlife to ionising radiation requires estimation to be made in a wide range of radionuclides to organism species and requirements for large datasets, which must meet specific criteria (Beresford and Willey, 2019) and the CRs approach is limited in that it is impossible to determine CRs for every specie. In the food chain, concentration ratio is often referred to as transfer factor and its ratio of the equilibrium activity concentration in plant (edible parts) to that of water or soil (or other exposure pathways: sediment, ingestion/ dietary pathway), which is also referred to as bioconcentration factor (IAEA, 2010; Howard et al., 2013; Beresford and Willey, 2019). For fruits, fresh mass to dry mass is considered, since fruits are consumed fresh (IAEA, 2010). Previous studies on tropical transfer established several general features of concentration ratios (CRs) which include

- That soil type is one of the dominant factors affecting soil-plant radionuclide transfer (Twining et al., 2012).
- No systematic difference between radionuclides transfer between climatic zone except extreme values from particularly tropical environments (Twining et al., 2012). However, according to Twining et al. (2012) and Uchida et al. (2007), tropical transfer values were higher compared to temperate radionuclide transfer.
- That chemical factors such as pH affects the transfer of Cs and Sr especially in tropical system. For example, low pH increases Cs and Sr availability (Twining et al., 2012).
- That increased K and Ca concentration in soil will decrease plant uptake of Cs and Sr respectively by competitive inhibition by analogous elements (Twining et al., 2012).
- Some species of crops typically showed high transfer factor than others (e.g. vegetable higher transfer than fruits) (Twining et al., 2012).

- If an unusual high or low CR for a nuclide is observed in one crop type in a soil, most likely that same general trend may be observed in other crops from that environment (Twining et al., 2012).
- CR values are nuclide specific and an anomalous CR values does not necessarily indicate that similar values would be observed by another radionuclide under the same condition (Twining et al., 2012).

CRs values in excess of one imply bioaccumulation of radionuclide activity and values less than one would mean strong binding of radionuclide to the soil particles or the plant is not actively accumulating the material (Twining et al., 2012).

2.7. Development of international databases

The IAEA and the International Union of Radiologist (IUR) have developed reports on radionuclide transfer parameter for generic wildlife groups and for the ICRP RAPs (IAEA, 2010) which are required to provide parameter values that can be used to quantify radionuclide transfer to non-human biota (http://www.wildlifetransferdatabase.org). These databases have been developed from IAEA TECDOCs and TRS reports (including TRS 472), for both food chain and wildlife (IAEA, 2010, 2014). IAEA programme on Development, Testing and Harmonization of Models and Data for Radiological Impact Assessment (MODARIA II) has established working groups (MODARIA II) which evaluates programmes on radionuclides exposures situation, effects on biota, transfer processes and radiological impact assessment (http://www-ns.iaea.org/projects/modaria/modaria2.asp?s=8&l=129). Currently, the IAEA working group four, has set up a sub-working group to report on transfer parameters in non-temperate and arid environment to provide harmonization to geographical biases in data for model development. Compilation of transfer databases have been developed from combination of stable elements and radionuclides data in Europe and North America (Uchida and Tagami, 2007; Beresford et al., 2008). However, according to Beresford et al. (2018), some variability might occur between stable element concentration and the corresponding radionuclides activity concentration. Although, this is the first time such discrepancy will be observed. Other than that, past literatures have reported, harmonisation between stable element concentration and radionuclides activity concentration (Uchida and Tagami, 2007; IAEA, 2009; Beresford et al., 2018).

2.8. Stable elements

Stable elements are chemical elements that have at least one stable naturally occurring isotope. The approach of characterising transfer using stable elements is not new especially where data for radioisotopes are not available. In Nigeria, the planned nuclear power plant is not operational, and the case study locations are not in heavily industrialized areas (Chad-Umoren et al., 2013), it will be expected that information on radioisotopes may not be available. Literature reports that the ratio of concentration of stable elements to radionuclides activity concentration (^{137}Cs & stable Cs) is not more than one order of magnitude for stable Cs and between (^{90}Sr & stable Sr ratio) consistent values have been obtained (Vera Tome et al., 2003; Tsukada et al., 2002; Tsukada et al., 2005; Uchida et al., 2006; Uchida and Tagami, 2007). Therefore, stable elements can be used to obtain transfer parameter for relevant radionuclide analogues. The stable elements with biogeochemical characteristics can be used for radioisotope when data for the stable elemental form are not available (e.g. Barium used as analogue to radium) (Tagami & Uchida, 2004). Radionuclide transfer from media to biota under equilibrium conditions have been estimated from concentration of stable elements in the biota and media (IAEA, 2010). The stable element of strontium and caesium can be used as analogues to the radioisotopes since they chemically behave in the same way (Uchida and Tagami, 2007) and because the range of CR values for both stable elements generally agrees with the corresponding radioisotopes (Uchida and Tagami, 2010). Similarly, Uchida et al. (2006) observed that 90Sr/Sr concentration ratios have a constant value in different components of rice plants in each sampling sites. The implication of this is that stable elements can be used as analogues for the long-lived radionuclides (Uchida et al., 2006). Stable elements and naturally occurring radionuclides which are related to long-lived radionuclides as well as rare elements which gives some ideas of the behaviours of actinides can be used where information are not available for the radionuclides (Uchida et al., 2006). Stable element transfer values are useful for evaluation of long-term transfer radionuclides in the environment and therefore, in this study, analysis of stable element of relevant radionuclide analogues was undertaken. However, stable elements cannot be used in an emergency or for short-lived radionuclides (Uchida et al., 2009). The use of analogue is not an accurate way of modelling but may be used to provide relevant information on environmental behaviour and in screening models if no other data are available.

2.9. Factors that influence transfer

Several factors influence the transfer of stable elements in the environment. These factors include soil factors, physical & chemical form of the radionuclide, plant species, plant compartment and farming practices (IAEA, 2004; IAEA, 2009). These factors introduce high variability in transfer parameter value (IAEA, 2004). Soil is the main source of stable elements for plants. In aerated (oxidizing) acid soils several stable elements become easily mobile and available while in poorly aerated (reducing) or alkaline soils, stable elements are generally less available (Kabata-pendias, 2010). Soil physicochemical properties such as soil pH, clay content & Cation Exchange Capacity (CEC), organic matter content affects the behaviour of radionuclides (Antoniadis et al., 2017). There are different soil types in Sub-Saharan Africa with varying mineralogy, pH value, Cation Exchange Capacity (CEC), and concentrations of analogue stable element (Twining, 2012).

2.9.1. Soil pH

Soil pH is one of the factors affecting stable elements transfer. For cations species of stable elements, lower pH value results in increase transfer, high mobility and availability while the opposite is true for anion species (Lee et al., 2009; Kader et al., 2016; Antoniadis et al., 2017). As pH increases, metal hydrolysis increases, and stable metal sorption is enhanced (Wang et al., 2015).

2.9.2. Clay content and Cation Exchange Capacity (CEC)

Soils with high clay contents especially 2:1 clay mineral retain larger concentration of radionuclides compared to sandy soils (Antoniadis et al., 2017). The effectiveness of clay soil to sorb metals depends on cation exchange capacity (CEC). High CEC can enhance clay retention capacity for stable elements (Antoniadis et al., 2017). Some stable elements can form strong covalent bond with clay lattice and readily become susceptible to clay retention and exhibit less transfer (Antoniadis et al., 2017; Rinklebe et al., 2017). For instance, some clay minerals which contained frayed edge surfaces can adsorb caesium far more than other soil types without such properties. Most clay mineral types including smectite, illite, vermiculite, allophane as well as oxides of silica, aluminium, iron and manganese have strong sorption ability for caesium (Koch-Steindl, 2001). Soils that have high content of illite,

smectite, vermiculites or mica absorbs large number of cations due to their negative charges (Koch-Steindl, 2001).

2.9.3. Organic matter

Organic matter (OM) in soils influences the transfer of stable elements in soils. Firstly, it increases plant viability, vegetative growth and enhances element concentration thereby affecting immobilisation and retention of elements in soil (Antoniadis et al., 2017). OM binds CEC to soils thus increasing the overall soil retention capacity (Shaheen et al., 2017). OM readily creates ligands with elements of sufficiently high molecular weight making them unavailable for root absorption (Antoniadis et al., 2017). Other Factors that influence transfer include plant species, cultural and farming practices. Some crops usually have high concentration ratios for a range of radionuclides than do other types (e.g. Leafy vegetables compared to fruits) (IAEA, 2009; Twining et al., 2012). Nutrient status of farmlands and animals may affect transfer of a range of radionuclides (Twining, 2012). However, no systematic difference in concentration between climatic regions has been highlighted, but extreme values have been observed, especially in the tropics (IAEA, 2009; Hirth et al., 2014). However, Wasserman et al. (2008b) has argued that climate play a role in radionuclide behaviour. Organic matter reduces anions adsorption because they form organic coatings on the surface anion adsorbing clay mineral (Koch-Steindl, 2001).

2.9.4. Elemental analogues

Chemical properties of elements follow well-established patterns, and this can form the basis for identifying potential analogues. Elements in same group in the periodic table display similar chemical behaviour because of the same number of outer electrons. In soil, the uptake or transfer of elemental analogue is influenced by lack or excess of the essential one (IAEA, 2009). Common analogue pairs are K and Cs, Ca and Sr, Ba & Ra. Transition elements in the same period of the periodic table are also chemical like each other (Including lanthanides are oxidation state analogues) (IAEA, 2009). Elemental analogues chemical similarity does not mean the same behaviour in the environment. Differences in behaviour is larger with chemical group analogue compared with periodic analogue. If an analogue is lacking or in excess in a soil, it can affect the uptake or transfer of the radionuclide analogue (IAEA, 2009).

2.9.5. Application of fertilizers

The application of potassium fertilizers may increase the concentration of potassium ions in the soil. This in turn may increase the competitiveness of potassium with caesium in the soil to plant transfer. Consequently, it could increase desorption of ^{137}Cs exchangeable from soil into soil solution (Guillen et al., 2017). The application of potassium fertilizers to soddy-podzolic soils can reduce Cs uptake by plants and conversely its application to peaty soils can increase uptake of ^{137}Cs. Sometimes the effects are dependent on the rate of application of the fertilizer. However, the application of potassium fertilizers at an increased rate in most soils will result in reduction of ^{137}Cs transfer to plant (Guillen et al., 2017; 2018).

2.10. Climate change and radionuclide transfer

There have been several debates on global climate change, and recent assessments are reaching a compromise that global climate change is occurring. However, its magnitude and impact remain obscure. No doubt, all aspects of the natural environment will be impacted in one form or the other. Even after five decades of intensive research on radioecology, protecting humans and wildlife from the effects of ionising radiation is still faced with some uncertainties (Dowdall et al., 2008). There are postulations that climate change will impact on soil to plant transfer. Especially when all the variable influencing transfer are directly or indirectly climate dependent. Two major climatic variables greatly affected by change in climate are temperature and rainfall which in turn would affect radionuclide transfer (Dowdall et al., 2008). The nature and extent to which predicted changes might have an impact are so diverse that it appears only a few aspects of nature may not be affected by climate change (Dowdall et al., 2008). The fundamental processes which control radionuclide transfer are not new to the radioecology. However, the key variables of climate change (precipitation, temperature, changes in soil properties, CO_2 level and UV-B exposure) will at one point or the other, far less or greatly affect the physiological and chemical processes that influence radionuclide transfer (Dowdall et al., 2008).

Although several predictions and potential impacts of climate change have been made. The magnitude of changes and impact will from one region vary to the other and impact on biota cannot be confirmed with certainty. Several factors, that affects soil to plant transfers are linked to physiological soil processes. These factors which include soil properties (pH, OM,

Clay content and mineralogy, CEC, moisture content, nutrient status as well as chemical concentration of analogue) are the major factors influencing radionuclide bioavailability (Frissel et al., 2002) Other factors such as ionic nature of soil solutions and plant species also influence transfer. Many of these factors are controlled by local environmental and climatic conditions such as precipitation and temperature (Dowdall et al., 2008). Precipitation as a driver of climate change affects radionuclide transfer in several ways (Armstrong et al., 1994) Precipitation intensity and soil resuspension can increase or decrease radionuclide transfer depending on the location/ region. In precipitation vulnerable environment including the arid and semi-arid region, increased rainfall, surface runoff may increase transfer. Resuspension, or rain splash is the most significant process by which actinides and other radionuclides are transferred to plant surfaces (Hakonson, 2007). Soil texture, rainfall intensity, duration and frequency has been predicted to change and these factors together affects resuspension and hence radionuclides transfer may change (Dowdall et al., 2008). Soil moisture content which sometimes may be related to amount of precipitation also affect radionuclide transfer. Livens and Loveland. (1988) enumerated clay mineral contents, pH, OM content, $NH4^+$ and potassium as factors which affect caesium transfer. Several studies have been done on the role of soil organic matter on the behaviour of Cs in soil. The transfer of ^{137}Cs from soil to plant is relatively high in high organic soils (Absalom et al., 1999; Sanchez et al., 1999). Radiocaesium shows high affinity for humic and clay substances and in the process bind to the frayed edge sites (clay specific site) of the clay minerals especially illite and vermiculites (Valcke and Cremers, 1988). Some ions like K^+, $NH4^+$, Rb^+ compete with Cs for absorption to clay mineral sites. Only in soils high in $NH4^+$, low clay content, low K^+ concentration in the soil solution and low organic matter, is Cs sorption controlled by clay minerals (Rigol et al., 2002). However, excessive OM and low clay content may result in Cs been absorbed to a nonspecific site. Staunton et al. (2002) stated that high organic matter will reduce the attraction of clay minerals for radiocaesium and enhance plant uptake. Soil organic matter contribute significantly to radionuclide soil to plant transfer by affecting CEC, pH, redox potential, moisture content as well as the soil structure (Stevenson, 1994). CEC in soil is dependent on the soil organic matter 40-50% and 30-60% (Loveland and Webb, 2003). Changes in OM in the soil would affect the CEC, pH, and the soil buffering capacity (Eshetu et al., 2004). Soil organic matter increases the amount of water available to plant, soil bulk density and aggregation (Emerson and McGarry, 2003).

The soil is affected by changes in climate directly or indirectly. Direct impact may be due to modification in water balance, temperature changes and indirectly through growth condition changes for plants and soil organism's activity. Soil responses to changes in environmental conditions takes time. When some factors change within days (water, temperature, pH), some may take a much longer time or decades (OM) and others such as weathering processes may take centuries and sometimes rarely occur (Koch-Steindl, 2001).

2.11. Conclusion

European models are calibrated for undertaking assessment in Europe and wider applicability of these models must be established. To improve model reliability and suitability for wider use, there is a need to apply the model to data from other regions (including Sub-Saharan Africa). The literature review highlighted the development of radiation protection system for both human food chains and wildlife, as well as radionuclides transfer and modelling. Furthermore, the review established that stable elements concentration can be used for the purpose of radiological assessment especially where data on radionuclides are not available. Similarly, the literature review highlighted a number of factors responsible for variation observed in transfer parameters including the effects of climate change and finally, it recognised that both food chain and wildlife radionuclide approaches have been applied to other regions but little evidence to date to establish that assessment approaches are applicable to SSA.

3. RADIONUCLIDES TRANSFER DATABASE FOR SUB-SAHARAN AFRICA

3.1. Abstract

This chapter reports the development of the first radionuclide transfer database for the Sub-Saharan Africa. To facilitate wildlife dose assessments and the modelling of radionuclide transfer through human food chains, radionuclide transfer databases are required both for wildlife and food crops. The Sub-Saharan Africa database (SSAD) was developed using systematic review and this covered both published and unpublished sources. It focused on chemical elements likely to be considered within radiological assessments and, in the case of wildlife, marine, freshwater and terrestrial ecosystems to develop the transfer parameter database (Sub-Saharan Africa database (SSAD). Searches of six databases (including Web of Science all database, Springer Link, Scopus, Science direct, ProQuest, Google Scholar) were undertaken and the searches of all publication databases returned a total of 2941 articles with data related to radionuclides/stable elements transfer in SSA, but many of these articles did not meet the inclusion criteria and were discarded. The final SSAD was compiled with data from approximately 211 articles. CRs values were compiled for thirteen wildlife groups (including amphibian, annelids, arthropod, crustacean, fish, grasses, herbs, grasses and herbs, macroalgae, mammal, mollusc, sea grass and corals and tree) and for 36 elements (12 radionuclides and 24 other elements). In the case of the food crops, CR compilations were made for nine food crop categories (including cereal, fruit, leafy vegetable, legume, maize, vegetable, root, tuber and other vegetable) for 28 elements (8 radionuclides and 20 other elements). Generally, for wildlife, there was no consistent pattern between CR values for SSAD and IAEA. For food crops CRs were higher in SSAD compared to IAEA values and differences were between 1-3 orders of magnitude. In both cases (wildlife and food crops), CR values for SSAD were different compared to IAEA CRs.

3.2. Introduction

Environmental assessments to evaluate potential risks to humans and wildlife always involve modelling to predict contaminant exposure through major pathways (Yankovich et al., 2013). Many of the models which have been developed require input of parameter values including Concentration Ratios (CRs) to estimate the concentrations of contaminants in biota based on measurements of concentrations from the environmental media (water, soil) (Yankovich et

al., 2013). The evaluation of models used in conducting environmental assessment has identified the transfer parameter as a major driver of variability between model prediction (Beresford et al., 2008a; Beresford et al., 2008b; Beresford et al., 2008c; Beresford, 2010; Yankovich et al., 2010; Yankovich et al., 2013). A number of transfer parameter databases have been compiled including the IAEA wildlife transfer parameter handbook (Howard et al., 2013) as well as the transfer parameter compilation report for the Reference Animals and Plants (RAPs) (Strand, Beresford et al. 2009), but for SSA, this is the first compilation of transfer parameter database and without this database, the assessment of radionuclides transfer within the region may be challenged. The Sub-Saharan Africa has several mineral deposits (ranging from crude oil and gas, uranium, gold, bauxite, tin, lead and coal) (Olawuyi, 2018). According to IAEA. (2014), about 30% of global oil and gas discoveries made over the last five years have been in SSA, reflecting growing global appetite for African resources. The overall mining activities and oil & gas legacies in the region, has resulted in the release of contaminations, stable elements and radionuclides (including naturally occurring & anthropogenic) (Ikingura and Akagi, 1996). With the increasing level of contaminants from mining legacies and potential developments of nuclear programmes in the region, radionuclide releases must be assessed. Systematic review is a type of research method that uses transparent rigorous methodologies to locate and synthesize all available primary research on a specific research objective (Mani and Ginier, 2016).

The approach of collating data to develop a radionuclide transfer database is not new, it has been used in the development of several databases including the wildlife transfer database (Copplestone et al., 2013). The IAEA Technical Report Series (TRS) Publication/Handbook of parameter values for the prediction of radionuclide transfer to wildlife (Howard et al.,2013: Yankovich et al., 2013), the ICRP Publication 114, Environmental protection: transfer parameters for Reference Animals and Plants (ICRP,2009), and Wood et al database of transfer parameters for reptiles (Wood et al., 2010) were all compiled using this approach. Assessing the impact of ionising radiation on humans and wildlife requires a method to quantify radionuclides in the organisms (Brown et al., 2008). Popular among the methods is the use of the equilibrium concentration ratios (Howard et al., 2013). The primary data collated in the database were the biota to media concentration ratios obtained from online database sources (Wood et al., 2010). It is almost impossible to consider all living organisms

in all environments, as such, most organisms are often represented with a set of default reference organisms (Larsson, 2004). For the different habitat types (marine, terrestrial, freshwater and estuarine ecosystem, different databases have been developed. Databases of radionuclide transfer are developed with data from both radionuclide and stable elements (Copplestone et al., 2013). Most sources of data used in transfer database compilation have been obtained from peer reviewed literature, conference paper and other published and unpublished sources (Copplestone et al., 2013). Stable element data are often used when transfer data are not available for the radionuclide and when data are from uncontaminated sites (Sheppard and Evenden, 1988). Concentration ratios for stable elements are conservative when used to represent radionuclides with relatively short radiological half-lives and long biological half-lives as decay of the short-lived radionuclides can significantly reduce their concentration in biota tissues (NCRP, 1996; IAEA, 2009). Under equilibrium conditions i.e. long-time contact with the environment, radionuclides behave similarly to their naturally existing isotopes and as such their naturally existing elements can be suitable analogues (IAEA, 2009). But under accidental discharge or in contaminated environments CR values will often be higher than their existing stable element due to different mobility in soil to organism system.

3.3. Materials and Method (search strategy and selection criteria)

Systematic review was undertaken using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (Moher, Shamseer et al. 2015) which suggest that systematic reviews be based on a protocol that describes the rationale and planned method of the review. The procedure described in PRISMA was adopted and an online search in the following databases were undertaken (Web of Science all database, ProQuest, Scopus, Springer Link, Science direct and other search engines including Google Scholar for articles published from January 1960 to March 2019, using well defined search criteria. The review focused on 48 Sub-Saharan Africa countries and search terms were carefully selected according to PECO (Population, Exposure, Comparison, Outcomes), a widely used systematic review protocol (CEE, 2013; Kitchenham and Charters 2007). According to the PECO framework, population was represented by the geographical region (the Sub-Saharan Africa countries). The Exposure term represents major contaminants (the stable elements OR essential elements OR radionuclides OR heavy metals) and the comparison component was

the concentration ratios (CRs) OR Transfer factors OR activity concentration and outcome was represented by human food chains and wildlife species and other contamination or toxicity effects. The search terms developed following the PECO framework includes ''radionuclide* OR stable element*OR essential element*OR stable isotope* OR trace element* OR heavy metal*AND activity concentration* OR transfer factor* OR concentration ratio* OR bioavailability* OR bioaccumulation* OR bioconcentration* OR biota concentration* OR soil to plant transfer* OR elemental transfer to animal* AND Sub-Saharan Africa* OR West Africa* OR East Africa* Central Africa*OR Southern Africa*''. Searches were also conducted using the individual countries and individual elements basis. The key search terms were applied in all the six databases and a quick scan of journal title and abstract were performed to select articles that may be relevant. The wildcard (*) is interpreted as a substitute from any number of letters. For example, Niger* returns results containing Nigeria, Niger delta etc. it works best when there is at least 3 characters before the wildcard operator. The? wildcard entered in a search is interpreted as a substitute for any single letter. For instance, a search for hea? Will return only results that contain (head, heat, heal). The multiple operators used in searches worked in the order of NOT, OR, AND. The operators work for both words before and after except for NOT (which only work for word after). OR operator allows results to return either of the terms (e.g. Rice OR Maize returns ''Rice'' OR'' Maize''). The NOT operator excludes results that contains the term following the NOT, West Africa NOT North Africa will return searches which include ''West Africa'' but excludes ''North Africa''.

3.3.2. Selection criteria

To select relevant articles, a selection criterion which defined an inclusion and exclusion criteria is highlighted below. Articles selected included

(1) studies carried out in the Sub-Saharan Africa
(2) articles that report activity concentration in Biota (plants or animals/ wildlife) and in the media (soil, air, water and sediments)
(3) articles that report concentration of stable elements/radionuclides /heavy metals/ trace or essential elements. Such elements considered included (Tritium, Carbon-14, Cobalt-60, Iodine-131, Iodine-133, Caesium-134, Caesium-137, Caesium-133, Xenon-133, Xenon-135, Krypton-85, Ruthenium(Ru), Rhodium(Rh), Palladium(Pd), Technetium(Tc), Molybdenum(Mo), Cobalt(Co), Lanthanum(La), Zirconium(Zr),

Neodymium(Nd), Europium(Eu), Niobium(Nb), Promethium(Pm), Samarium(Sm), Praseodymium(Pr), Curium(Cm), Americium(Am), Chromium(Cr), Lead(Pb), Nickel(Ni), Zinc(Zn), Manganese(Mn)Yttrium(Y), Cerium(Ce), Plutonium(Pu), Neptunium(Np) Selenium (Se), Tellurium (Te), Antimony(Sb) Strontium(Sr), Barium(Ba) Caesium (Cs), Rubidium(Rb), Iodine(I) and Bromine(Br), Uranium(U), Thorium(Th), Radium(Ra).

(4) Articles with data that can be used to calculate Concentration Ratios (CRs) or distribution Coefficient (K_D) for a given food crops or wildlife species.

Assessment of outcome included tissue or whole-body concentration values. Articles were assessed based on the presentation of report of tissue and whole-body mass and dry or fresh mass concentration of the organism. A quick scan of the article's abstract was performed, and potential articles which contained usable data were selected. The search term was refined, and the refined term was applied to databases. In the selected articles, some were excluded on the basis that they did not contain enough information to be used to estimate CRs. Only studies that contains data that can be used to calculate concentration ratios (CRs) were included.

3.3.3. Data extraction and manipulation

For data extraction, the focus was on the activity concentration reported for environmental media and activity concentration reported for biota. These data were imported from the article into an excel spreadsheet. There were calculations and assumptions made at the stage of the data extraction and handling of summarised data. First, the number of observations were clearly stated and where there was obscurity in the number of observations(n-value) the following assumptions and guiding rules were made:

(1) n=1 was assumed where the author did not specify the number of sampling observations and when mean and standard deviation were not given

(2) n=3 was assumed, where the author collected many samples, but the specific number of sampling observations were not specified but the mean and the standard deviation were highlighted. N=3 was assumed because this is the minimum number of observations required to estimate standard deviation as well as the minimum value that would not over-estimate statistical parameters of the data (Wood et al., 2013)

(3) if the number of observations equalled 2, and the range of activity concentration were stated for the environmental media, both minimum and maximum concentration ratios were determined and added to the database (Wood et al.,2013)

(4) If number of observations were greater than 1(N>1) and biota and media activity concentration standard deviation were given, the concentration ratios standard deviation (CRSD) values were estimated with the following equation

CRSD = CRwo-media × SQRT ((Wildlife SD)/(Wildlife Activity Concentration))^2+〖((Media SD)/(Media Activity Concentration))〗^2

(5) Limit of Detections (LODs) It is common practice to find data which were below the limit of detection in environmental research. Typical mean and standard deviation of data containing values below LOD may be affected, if the <LODs value were ignored or simply replaced by absolute values which was common practice in some literatures. Here, where the limits of detection were given and <LODs values were stated, the less than values were simply replaced by an arbitrary small value or half the limit of detection. Wood et al, (2011) suggested more evidence-based survival analysis method when there are several <LODs data. However, the reason for adopting this approach was because data with <LODs were very small (Albaladejo and Martin-Fernandez, 2013)

(6) Sediments activity concentrations were not used to estimate concentration ratios. One reason was because they gave extremely large CRs. The second reason was that, CRs in IAEA publications were estimated with activity concentration of water and not sediment so to ensure homogeneity of data comparison, sediment concentration data were discarded. Although, the distribution coefficient (K_D) was estimated where sediment and water concentrations were given.

(7) Median concentrations as well as geometric mean concentrations were not used to estimate CRs to ensure homogeneity of data comparison with IAEA publications.

All references and calculations were maintained on the database to ensure easy verification of data from source documents. All data extracted were scrutinized to ensure overall data homogeneity by checking units of measurements and ensuring that dry mass to fresh mass were converted for wildlife and fruits and fresh mass to dry mass for other food crops and

vegetables (IAEA, 2009). Biota organism's tissue values, were converted to a whole-body concentration, using appropriate conversion factors (Yankovich et al., 2010).

3.3.3.1. Conversion of dry or ash mass (DM) to fresh mass (FM)

The calculation of CRs required fresh mass whole body concentrations (Beresford et al., 2008; Wood et al., 2010). Conversion needed to be made for whole or tissue concentrations reported in literature as dry mass. To convert the dry mass to fresh mass the dry matter content of the tissue or whole organism was determined. Conversely, where concentration has been stated in literature in dry mass (wildlife), this was simply converted to fresh mass CR. From dry mass to derive the fresh mass, multiplication by the dry matter content was applied. Note, fresh mass concentration is always lower than the dry mass concentration.

3.3.3.2. Converting tissue data to whole body activity concentration

Data were reported in tissue or whole-body activity concentration. In most cases, in which specific tissue data were reported, they were required to be converted to the whole-body concentration (Yankovich et al., 2010; Beresford et al., 2008) for CRs calculation using appropriate conversion factors given in Yankovich et al. (2010). Generally, specific tissues for which data were reported were those that were known to be major target tissues for an element and those that were major contributors to the whole-body burden for an element (Wood et al., 2010). These tissues include kidney, liver, muscle and bone for animals. Data sets of appropriate tissue to whole body conversion factors for freshwater, marine and terrestrial environments exist in publications (Beresford et al., 2008; Yankovich et al., 2010) and the conversion factors from Yankovich et al. (2010) were used in this study.

3.3.4. Data synthesis

The extracted concentration ratios were used in the development of the Sub-Saharan Africa database (SSAD) and this database consists of wildlife transfer and food chain transfer parameters. Data extracted were maintained in a comprehensive Microsoft excel spreadsheet. Standard data summarisation technique described in Wood et al. (2013) was applied to data with n>1 value to produce individual concentration values which can be statistically compared to those from standard international datasets. The Wood et al. (2013) summarised spreadsheet was applied and individual concentration estimates of organisms were produced (Wood et al., 2013). The information recorded in the database include, habitat, organism, wildlife group or food crop types, ICRP RAPs (life stage, scientific name,

common name, the study types, measurement made, date and location, tissue type, media type, CR value, SD CRs and element type. Figure 3.3a shows the systematic review protocol

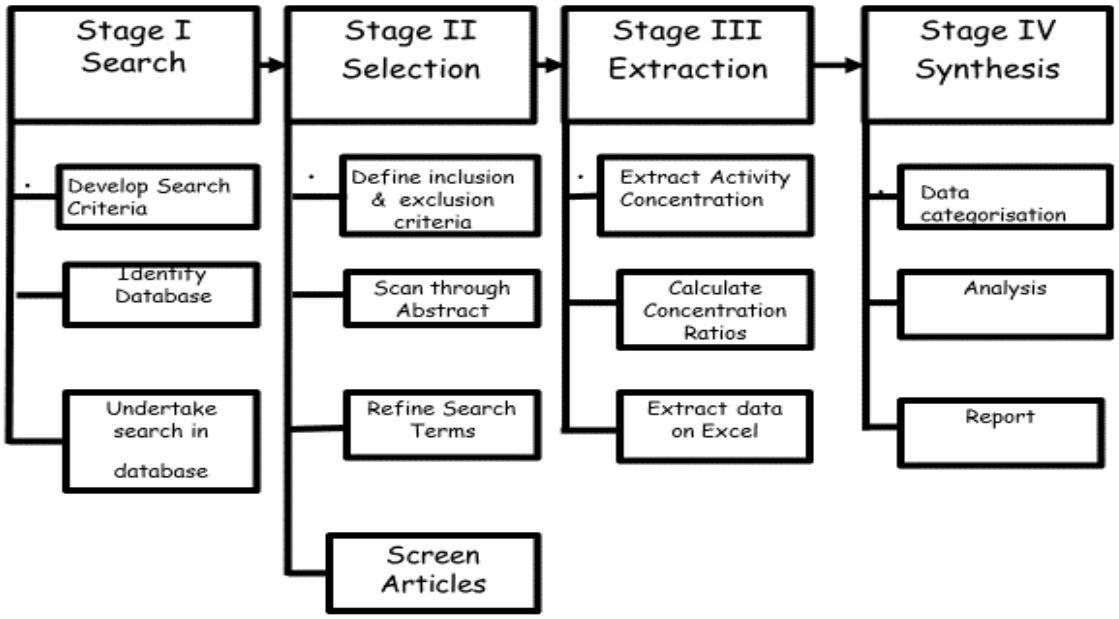

Figure 3.3a. The systematic review protocol (Kitchenham and Charters, 2007)

3.3.5. Systematic review flow chart

The search conducted returned a total of 2941 journal articles describing one, two or three of the core parameters (Sub-Saharan Africa, radionuclides and concentration ratios). About 2702 articles were removed due to insufficient information to estimate concentration ratios. Furthermore, 28 articles were removed for duplication. The remaining 211 articles were used for the development of the SSAD, after an independent random review of 20 articles by a second reviewer, and all independently randomly reviewed articles were included for the development of the transfer database. Figure 3.3b presents the review process flow chart.

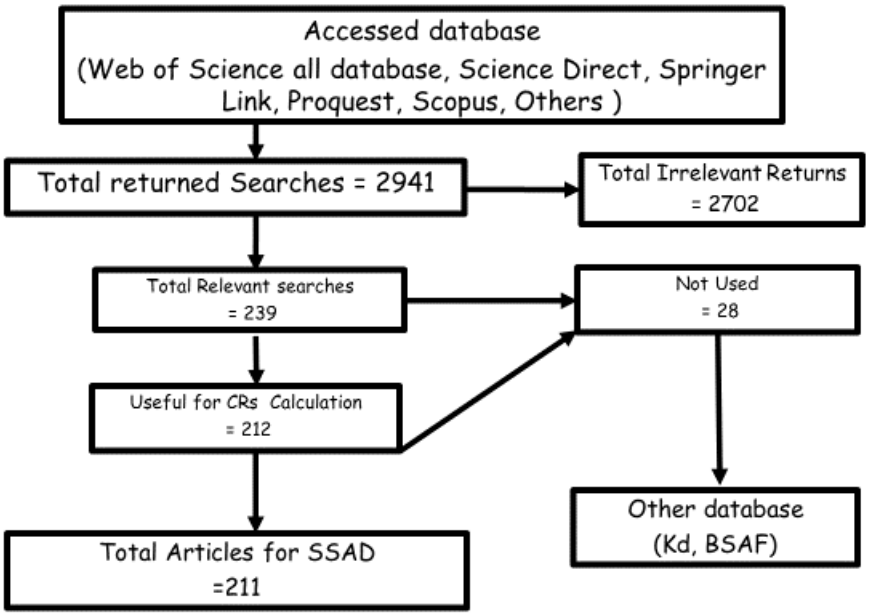

Figure 3.3b. The flow of the systematic review process & summary of selection (Rothenberg et al., 2014)

3.3.6. Quality assessment, data review and primary data source

The data quality was assessed using the Hawker et al. (2002) framework which provides for methodological appropriateness of included articles (Hawker et al., 2002). This process involved specifying criteria for accepting and rejecting journal articles and established guiding rules to follow in implementing the systematic review. See criteria for inclusion and guiding rules in sub sections 3.3.2 and 3.3.3 respectively. Articles that met the criteria for inclusion were scored good (high score). Articles that have not met the criteria were rated poor and discarded (scored low). Some articles reported only biota concentrations or only on media concentrations, they were rated fair and kept for possible use in Residual Maximum Likelihood (REML) (scored moderate). According to Kitchenham and Charters. (2007), assessment of data quality standard reduced researcher's bias and improved the quality of the review. To improve quality, data quality was assessed by second reviewer including my research supervisors. Areas of ambiguity for correction were highlighted and corrections were implemented. An independent second reviewer made an independent assessment of inclusion and exclusion decisions on 20 articles randomly selected from the 211 journal articles. The second reviewer's judgement reduced researcher's bias and ensure decisions for

inclusion and rejection were based on good judgement. In each case, not less than two persons judged articles for inclusion (CEE, 2013).

3.3.7. Research data analysis

Basically, there were two data categories food chain and wildlife transfer data. Prior to the data analysis using SPSS, we extracted individual stable elements/ radionuclide concentration ratio from the IAEA and SSAD databases and further run the values using the Wood et al. (2013) spreadsheet. The spreadsheet enables concentration ratios with n value greater than one to be spread out to obtain individual CR from summarised datasets. The individual CR values from IAEA and SSAD were collated on excel spreadsheets and the test of statistics performed. Organisms data within the SSAD were compared to data from IAEA publications by element and habitat. Since CRs values always tend towards log normal distribution, geometric mean (GM) and geometric mean standard deviation (GMSD) were estimated, which provide better statistical measurement of bound of confidence interval for a lognormal distribution (Wood et al., 2013).

3.3.8. Stable elements as radionuclide analogues

Stable elements have been used as radionuclide analogues for radioisotopes to provide transfer data for both human food chain (Shepherd et al.,2009; Uchida and Tagami, 2010) and wildlife (Takata et al., 2010; Howard et al., 2013; Guillen et al., 2018). Data on radionuclides transfer are limited in SSA due to less development of nuclear programmes and nuclear weapon testing in the region. However, there are long standing contamination issues on mining legacies and oil exploration in SSA. Therefore, a common approach is to measure stable elements as analogues of radionuclides of interest. This approach has been adopted in this study and in many previous literature publications (Uchida et al., 2007) and even in the development of international transfer databases (Howard et al., 2013) and models such as the ERICA (Brown et al., 2008; Brown et al., 2016). Concentration Ratios (CRs) value of radionuclides and stable elements are comparable and usually not different (Vera tome et al., 2003) and as a result stable element can be used as substitutes where radionuclides data are lacking (Uchida and Tagami, 2010).

3.4. Analysis of data

The first step of the statistical analysis ensures the sorting of the data sets into groups. Three basic groups were identified to include terrestrial wildlife group, terrestrial food crops and marine organism's group. There were different other organisms' sub groupings within the major groups. The analysis compared the SSA data with dataset from IAEA publications. The test of normality was undertaken using descriptive statistics in SPSS. The normality test of the CRs data shows that the data were not normally distributed and the Kolmogorov-Smirnova, Shapiro-Wilk were not significant for most of the data tested. The histogram and Q-Q Plot of CRs data confirmed that most data were not normally distributed. See figure 3.3c and 3.3d of the histogram and Q-Q plot of the normality test

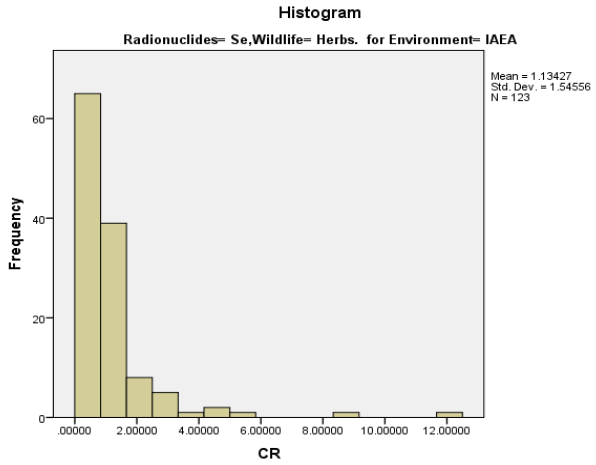

Figure 3.3c. Histogram test of normality

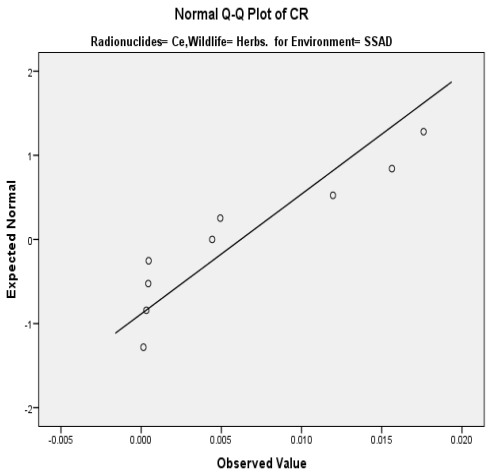

Figure 3.3d. Q-Q plot test of normality

Figure 3.3c and figure 3.3d are the histogram and Q-Q plot of the normality test. Log transformation of the data was undertaken, and normality of the log transformed data tested, the result shows that more of the transformed data were normally distributed compared to the untransformed data. The histogram and Q-Q plot in figure 3.3e and 3.3f respectively revealed the degree of normal distribution of the data. Parametric test using one-way ANOVA was chosen to compare the mean of the concentration ratio data of both IAEA and SSAD. Analysis of variance was performed to determine the variability among the mean in each group and to understand if the differences between IAEA and SSAD concentration ratios were significant and different. To further establish the degree of significant difference between specific groups, post hoc test was carried out.

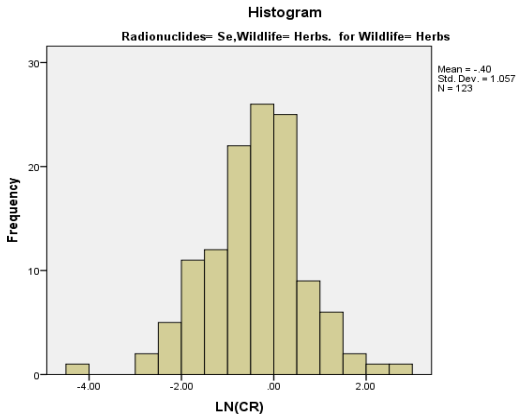

Figure 3.3e. Histogram of Log transformed data.

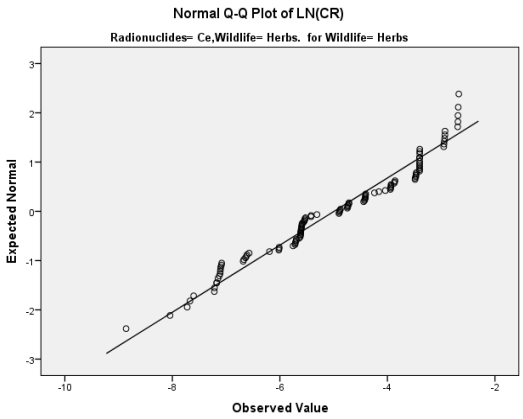

Figure 3.3f. Q-Q plot log transformed test of normality.

3.4.1. Summary statistics for terrestrial wildlife concentration ratios

Table 3.4.1a. Statistical table of significance for terrestrial wildlife for cerium, cobalt and caesium.

Element	Wildlife	Location	N	Mean	SD	DF	F	P
Ce	Herbs	IAEA	106	1.65E-02	1.88E-02	1	2.66	0.11
		SSAD	9	6.21E-03	7.02E-03	113		
Co	Grasses	IAEA	57	4.53E-02	8.76E-02	1	1.48	0.23
		SSAD	30	2.54E-02	2.49E-02	85		
Cs	Herbs	IAEA	103	9.53E-02	2.75E-01	1	0.33	0.57
		SSAD	19	5.90E-02	3.05E-02	120		

There was no statistically significant difference between elements-organism combinations at (p=0.05) level of significance. The summary of the descriptive statistics for terrestrial wildlife is contained in Appendix 1. No specific pattern has been observed with the analysis of variance for wildlife between the two groups (IAEA and SSAD dataset) in all these elements and wildlife combinations: Ce (Herbs), Co(Grasses), Cs (Grasses), Cu (Grasses, Tree), Eu(Herbs), Mn (Annelid, Tree), Mo (Grasses, Herbs), Ni (Amphibian, Grasses), Pb (Annelid, Grasses,), Se (Grasses), Sr (Herbs), U (Grasses, Tree), U-238 (Grasses, Herbs), V (Grasses, Tree), were not significant. Table 3.4.1b indicates significant difference between terrestrial wildlife.

Table 3.4.1b. Statistical table of significance of CRs for different terrestrial wildlife. Note; Se=selenium, Cs=caesium and U= uranium (SD= Standard deviation, DF= Degree of freedom)

Element	Wildlife	Location	n	Mean	SD	DF	F	P
Se	Mammal	IAEA	40	2.36E-01	2.54E-01	1	33.08	0.00
		SSAD	40	4.75E-03	6.83E-03	78		
Cs	Grasses and Herbs	IAEA	16	5.79E-02	2.75E-02	1	16.54	0.00
		SSAD	17	2.47E-02	1.88E-02	31		
U	Herbs	IAEA	92	9.64E-02	1.09E-01	1	9.52	0.00
		SSAD	15	9.26E-03	1.21E-02	105		

However, in the following elements and wildlife combinations: Co(Herbs), Cr (Amphibian, Annelid, Arthropod, Tree), Cs (Grasses and Herbs, Tree), Mn (Amphibian, Arthropod, Grasses), Ni (Annelid, Arthropod, Tree), Pb (Amphibian, Arthropod, Mammal, Tree,), Ra-226 (Grasses, Grasses and Herbs, Herbs), Rb (Grasses, Herbs, Tree), Th (Grasses, Grasses and Herbs, Herbs), V (Amphibian, Annelid, Arthropod, Grasses), Se (Mammal), Sr (Tree), U (Herbs), significant differences were observed between IAEA and SSAD concentration

3.4.2. Analysis of variance for fresh water and marine wildlife

Individual statistics of the concentration ratios of fresh water and marine wildlife are presented in the Table 3.4.2a. The analysis of variance for barium for the marine wildlife group shows significant difference for crustacean and macroalgae but for fish no significant difference was observed. Conversely, for cobalt, significant difference was observed between IAEA and SSAD concentration ratio for fish dataset, but no significant difference was observed in crustacean and macroalgae. For Mo, Rb and Se, the analysis of variance in fish data revealed that there was a significant difference in concentration ratio (CR) values between the two groups (IAEA and SSAD). Similarly, for Mo and Sb in macroalgae group of organisms, significant difference was also observed. For uranium and strontium, there was no significant difference in fish data analysed between IAEA and SSAD data as observed in figure 3.4.2b.

Table 3.4.2a. Barium and Cobalt mean CRs for freshwater and marine wildlife

Element	Wildlife	Location	N	Mean	SD	DF	F	P
Ba	Fish	IAEA	15	9.59E+00	7.15E+00	1	1.37	0.24
		SSAD	409	3.53E+02	1.14E+03	422		
	Macroalgae	IAEA	9	1.94E+03	1.15E+03	1	34.78	0.00
		SSAD	12	3.23E-01	2.15E-01	19		
Co	Fish	IAEA	93	5.72E+02	1.27E+03	1	17.61	0.00
		SSAD	252	1.36E+02	6.39E+02	343		
	Macroalgae	IAEA	135	5.10E+03	9.96E+03	1	3.12	0.08
		SSAD	12	8.40E+00	8.63E+00	145		

Fish-Ba, Co

The values of CRs for Ba presented in this study in table 3.4.2a were derived from data (n=409) in seven articles (Retief et al., 2009; Jordan, 2012; Otachi et al., 2015; Jooste et al., 2015; Leopold et al ., 2009; Taiwo and Awomeso, 2017; Afolayan, 2018). The Ba CR is 36 times greater than IAEA value (based on n=15). The Co CRs for SSA were derived from data (n=252) presented in eleven articles (Adeyeye,1994; Asaolu and Olaofe, 2005; Olawale and Musa, 2005; Retief et al., 2009; Oyoo-Okoth et al., 2013; Cheyns et al., 2014; Muposhi et al., 2015; Sone et al., 2017; Utete et al.,2018; Ezemonye et al., 2019). The mean Co CR for SSA was 4 times lower than the IAEA value (n=93).

Table 3.4.2b. The mean concentration ratios of fish in different stable elements

Element	Wildlife	Location	N	Mean	SD	DF	F	P
Mo	Fish	IAEA	23	1.59E+00	4.40E-01	1	8.23	0.01
		SSAD	70	1.41E+01	2.09E+01	91		
Rb	Fish	IAEA	20	6.46E+01	3.05E+01	1	12.32	0.00
		SSAD	34	2.05E+02	1.76E+02	52		
Se	Fish	IAEA	41	1.01E+03	6.83E+02	1	90.16	0.00
		SSAD	44	3.46E+01	3.34E+01	83		
Sr	Fish	IAEA	22	2.05E+01	2.82E+01	1	2.39	0.12
		SSAD	614	3.30E+02	9.37E+02	634		
U	Fish	IAEA	18	4.87E+00	6.23E+00	1	0.11	0.75
		SSAD	35	4.44E+00	3.58E+00	51		

Fish- Mo

The values of CRs presented for SSAD in table 3.4.2b was derived from data (n=70). This data came from four articles; Retief et al., 2009; Overah et al., 2012; Otachi et al., 2015 and Taiwo and Awomeso, 2017), their values were 9 times higher than values presented in IAEA data (n=23).

Fish- Rb

The values of Rb concentration ratios presented in this study in the Table 3.4.2b was derived from the article (Otachi et al., 2015) for n=34 number of observations, their mean CR value was 3 times higher compared to the mean CR for fish in IAEA data(n=20) data for Rb.

Fish- Se

Se CR values presented for SSAD in Table 3.4.2b was derived from data from three articles (including Retief et al., 2009; Overah et al., 2012 and Olabanji and Oluyemi, 2014), number of observations (n=44). SSAD CR value was 29 times lower than values presented in IAEA (n=40)

Fish-Sr

The values of CRs presented in this study in the Table 3.4.2b was derived from data presented for (five articles; Retief et al., 2009; Crafford et al., 2010; Jordan, 2012; Leopold et al., 2015; Sone et al., 2017) (n=614), the mean CR value was 16 times higher than values presented in IAEA (n=22)

Fish- U

The values of SSAD CRs presented for uranium in the Table 3.4.2b was derived from data presented for two articles (Retief et al., 2009; Sone et al., 2017) , (n=35), the mean value was in the same order of magnitude with values presented in IAEA (n=18). There was no difference and CR were comparable for both SSAD and IAEA data.

Table 3.4.2c. CRs statistical table of significance of macroalgae for Mo and Sb

Element	Wildlife	Location	N	Mean	SD	DF	F	P
Mo	Macroalgae	IAEA	89	2.38E+01	3.41E+01	1	5.67	0.02
		SSAD	12	2.12E-01	2.80E-01	99		
Sb	Macroalgae	IAEA	43	1.57E+02	2.35E+02	1	5.25	0.03
		SSAD	12	3.41E-02	5.37E-02	53		

Macroalgae- Mo

Values of CRs presented in table 3.4.2c was derived from data presented for (Boamposam,2009) (n=12), CR value was 112 times lower than values presented in IAEA (n=89).

Macroalgae- Sb

The values of CRs for both Sb and Co presented in this study were derived from data (n=12) from two articles (Boamposam, 2009; Taiwo and Awomeso, 2017). Mean value was (4593 and 607 times) lower than values presented in IAEA (n= 43, 135) respectively.

3.4.3. Analysis of variance for food crops

Table 3.4.3a. Statistical table of significance for Cobalt in food crops

Element	Food crops	Location	n	Mean	SD	DF	F	P
Co	Cereal	IAEA	65	3.65E-02	4.12E-02	1	5.92	0.02
		SSAD	16	6.98E-02	7.40E-02	79		
	Leafy Vegetable	IAEA	185	2.61E-01	2.02E-01	1	83.80	0.00
		SSAD	625	1.81E+00	2.30E+00	808		
	Maize	IAEA	77	4.06E-02	4.06E-02	1	4.31	0.04
		SSAD	47	7.71E-01	3.09E+00	122		
	Tuber	IAEA	56	7.46E-02	7.27E-02	1	4.38	0.04
		SSAD	203	1.25E-01	1.75E-01	257		

Table 3.4.3b. Statistical table of significance for caesium and strontium in food crops

Element	Food crops	Location	n	Mean	SD	DF	F	P
Cs	Root	IAEA	93	7.41E-02	1.43E-01	1	16.35	0.00
		SSAD	7	3.07E-01	1.96E-01	98		
Sr	Legume	IAEA	148	2.00E+00	1.32E+00	1	4.25	0.04
		SSAD	3	3.59E+00	5.37E-01	149		
Sr	Tuber	IAEA	106	2.47E-01	1.71E-01	1	131.31	0.00
		SSAD	4	1.58E+00	9.18E-01	108		

Table 3.4.3c. CRs statistical table of significance of other elements-food crops combinations.

Element	Food crops	Location	n	Mean	SD	DF	F	P
Co	Root	IAEA	16	1.54E-01	1.34E-01	1	1.43	0.23
		SSAD	138	3.30E-01	5.86E-01	152		
	Vegetable	IAEA	7	1.56E-01	5.60E-02	1	0.36	0.55
		SSAD	573	2.88E+00	1.20E+01	578		
Cs	Tuber	IAEA	138	9.46E-02	9.82E-02	1	2.09	0.15
		SSAD	4	2.33E-02	1.12E-02	140		
Sr	Leafy Vegetable	IAEA	217	1.98E+00	1.86E+00	1	0.16	0.69
		SSAD	17	1.79E+00	1.73E+00	232		
	Maize	IAEA	75	7.70E-01	6.00E-01	1	0.04	0.84
		SSAD	2	8.55E-01	7.78E-02	75		
	Vegetable	IAEA	19	1.03E+00	1.90E+00	1	2.45	0.13
		SSAD	7	2.35E+00	1.96E+00	24		
U	Root	IAEA	83	5.86E-02	9.37E-02	1	1.00	0.32
		SSAD	6	2.01E-02	2.15E-02	87		

Individual statistical results for food crops are contained in appendix 3. Co (cereal, leafy vegetables, maize, tuber), Cs (root), Mn (cereal, maize, root), Ni (cereal), Pb (legume), Rb (leafy vegetable), Sb (root), Sr (legume, root, tuber), U (vegetable), Zn (cereal) and all the stable elements - food crop combinations listed, showed significant difference in CRs values between IAEA and SSAD data.

Co- Cereal, leafy vegetable, maize

Values of Co for cereal in SSAD CRs presented in the table 3.4.3a were derived from data presented for (n=16). Mean SSAD CR value was 2 times higher than values presented in IAEA(n=65). Similarly, values of Co CRs presented in the Table 3.4.3a was derived from data presented for (n=625). Mean CRs value was 7 times higher than values presented in IAEA (n=185) for leafy vegetable. In the same vain, values of Co CRs presented for SSAD in the Table 3.4.3a was derived from data with (n=47) number of observations. The mean CR for SSAD maize was 18 times higher than values presented in IAEA (n=77).

Cs- Root, Sr- Tuber and U- Vegetable

Values of Cs CRs presented for SSAD in the table 3.4.3b was derived from data presented for (n=7) observations. Mean value of the root crop CR was 4 times higher compared to values presented in IAEA (n=93) for caesium. Similarly, values of Sr CRs presented for SSAD in the table 3.4.3b was derived from data presented for (n=4). Mean value was 6 times higher than values presented in IAEA (n=106) for tuber crops. Values of CRs presented for SSAD for legume in the table 3.4.3b was derived from data presented for (n=3) and value was slightly higher than values presented in IAEA (n=148).

However, for Ba (Leafy vegetable, Tuber, vegetable), Co (Legume, Root, vegetable), Cr (Cereal, Leafy vegetable,, Root, Tuber, Vegetable), Cs (Tuber), Mn (Leafy vegetable, Legume, Tuber, Vegetable), Mo (Leafy vegetable, Maize), Pb (Cereal, fruit, Leafy vegetable Maize, Root, Tuber, Vegetable), Rb (Root), Sb (Tuber), Sr (Leafy vegetable, Maize, Vegetable), U (Root, Tuber), Zn (Leafy vegetable, Maize, Root, Tuber, Vegetable), there were no statistical significance between IAEA and SSAD transfer parameter dataset.

Co- Legume

Values of CRs presented in this study in table 3.4.3c were derived from data presented for (n=27). Mean value was comparable to values presented in IAEA (n=105).

Cs- Tuber Sr- Leafy Vegetable U- Root Pb- Root, Cereal

Values of SSAD CRs presented in table 3.4.3c were derived from data presented for (n=4). Mean value was slightly lower than values presented in IAEA(n=138) for tuber crops. Values for SSAD CRs presented in the table 3.4.3c were derived from data presented for (n=17). The mean value of the CR was comparable to values presented in IAEA (n=217) for vegetable and were within the same order of magnitude. In addition, values of CRs presented for uranium in table 3.4.3c were derived from data presented for (n=6) for root crops. Mean value was slightly lower than values presented in IAEA (n=83). The values were within the same order of magnitude. Values of SSAD CRs presented for maize in Table 3.4.3c were derived from data presented for (n=2). Mean value was comparable to values presented in IAEA (n=75).

Figure 3.4 summarises the comparison of mean IAEA: SSAD CRs. There was no consistent pattern in the differences observed although the majority of crop mean CRs in SSAD were greater than those in the IAEA data compilation.

		IAEA:SSAD														
		Cs	Rb	Ba	Sr	Co	Cr	Mn	Mo	Ni	Pb	Zn	Sb	Se	Ce	U
Wildlife	Grasses					1.78E+00	1.33E+00	2.02E+00		1.27E+00	1.48E+00	2.03E+00				
	Herbs	1.62E+00													2.66E+00	1.04E+01
	Grasses & Herbs	1.34E+00														
	Tree						1.04E-02	4.01E-01		3.80E-02	1.01E-01	1.32E+00				
	Macroalgae			6.01E+03		6.08E+02			1.12E+02				4.59E+03			
	Amphibian						2.09E-02	1.97E-02		6.60E+00	5.22E-02	1.36E-01				
	Annelid						1.61E-01	1.65E+00		5.82E-02	5.69E-01	5.24E+01				
	Arthropod	.					5.93E+00	1.15E+02		1.28E+01	1.14E+01	8.58E+02				
	Crustacean			1.00E+02		2.11E+02										
	Fish		3.15E-01	2.72E-02	6.23E-02	4.19E+00			1.13E-01					2.93E+01		1.10E+00
	Mammal													4.96E+01		
Crop	Root	2.41E-01				4.67E-01										2.92E+00
	Tuber	1.57E-01				5.98E-01										
	Vegetable				4.38E-01	5.43E-02										
	Leafy Vegetable				1.10E+00	1.44E-01										
	Maize				9.01E-01	5.27E-02										
	Legume	5.59E-01														
	Cereal					5.23E-01										

Figure 3.4. Ratios of mean IAEA to mean SSAD concentration ratios for different organism-element combinations. The green markers indicate IAEA:SSAD ratios below 1, yellow markers indicate ratios between 1 and 10, orange markers indicate ratios greater than 10. Elements are grouped according to their periodic table groupings.

3.5. Discussion of results for terrestrial wildlife

The evaluation of stable elements need to be assessed based on scenarios and relative importance in contribution to total exposure of different wildlife groups for example, the CRs for tree in the terrestrial ecosystem and for the following stable elements (Cr, Mn, Pb, Ni, Cs, Sr, V and Rb) showed higher CR values in SSAD compared to the IAEA. The CRs values were between 1 to 3 order of magnitudes higher than IAEA and this may be due to trees being perennial crops with long life span and prolong exposure period for contamination by stable elements. The allometric approach relates body mass to life span and therefore uses biological variables or parameters to estimate concentration ratio. This would suggest that lifespan may have an implication on the overall radionuclide burden of wildlife (Higley et al., 2003; Beresford et al., 2004; Beresford et al., 2010). Besides, trees have deep rooting system which are capable of penetrating into the sub-soil and therefore greater access to nutrient (stable elements). In SSA, stable elements availability in the sub soil may be due to leaching (Gwenzi et al., 2015; Obiora et al., 2016) and with more erosion activity in SSA caused by heavy rainfall than for temperate region (Europe and North America). The concentration ratio of strontium is higher than caesium for tree and this may likely be due to strontium being calcium analogue and its required for the formation of tree bark and strong roots (Howard et al., 2013). For the arthropod(bee), higher transfer values may likely be attributed to specie migration which may likely result in specie exposure to environmental contaminants (Leita et al., 1996; Conti and Botre, 2001; Porrini et al., 2003). Heavy metals including chromium accumulate to reasonable extent in arthropod (bee).

Stable caesium in plants (Grasses, Grasses & Herbs, Herbs, Tree) presents an average concentration of 0.037mg/kg, and this compared to Beresford et al., 2018 plant stable caesium data (0.012mg/kg) comparatively of the same order of magnitude. Though stable strontium showed higher concentration ratios in SSAD data, CR value was within an order of magnitude higher than IAEA. The mean CR of stable uranium in SSAD for herbs were lower compared to values presented in IAEA and SSAD for the radioisotopes (^{238}U). Similar pattern was reported by Barnett et al. (2014) but for stable caesium in (wild grass and pine tree species) for which the mean of the stable element was lower compared to the

radionuclide(^{137}Cs) (Barnett et al., 2014; Thorring et al., 2016). Beresford et al. (2013) and Wood et al. (2013) also noted significant differences in radio and stable element data extracted from the wildlife transfer database. Beresford et al., (2018) observed low values for stable Cs and Sr compared to ^{137}Cs and ^{90}Sr. Higher CRs obtained from SSA for wildlife compared to IAEA may be attributed to a combination of factors explained in chapter two. This result aligned with Johansen and Twining, 2010 which demonstrated higher CRs from semi-arid Australia terrestrial wildlife and livestock compared to values from temperate environment.

3.5.1. Discussion of results for freshwater and marine wildlife

Due to the diversity of species and the range in physicochemical conditions in natural ecosystems, CRs data are often subject to variation and these may range from 1-3 order of magnitude even within similar species (Yankovich et al., 2013). Many aquatic organisms including some fish are filter feeders and tends to accumulate particles of stable elements especially reactive elements such as Cs, Sr, Ca, K, Ba (Howard et al., 2013). The aquatic CRs in this study were dominated by fish data and the highest CRs values were observed in Sr and Barium. This may likely be due to their ability to accumulate in many aquatic organisms. Secondly, strontium is also an important analogue to calcium which is essential element for the formation of strong tissues and bones in many aquatic organisms including fish. Major species of fish in the SSA include (*Clarias spp*, *Oreochromis spp*, common carp). They are basically bottom feeders but occasionally filter feeding on particulates in surface water (Menezes et al., 2010). For transuranic element(uranium), similarity in CRs values in the same order of magnitude was observed which may suggest a similar behaviour of transuranic in both SSA and IAEA aquatic environment. However, in contrast, Co and Se CRs have been relatively lower than values reported in IAEA. This may be due to water quality and other environmental variables (increased organic matter) can modify accumulation of metals in aquatic system. Interactions with other elements can increase or decrease Co and Se accumulation (ASTDR,2003; Hamilton and Palace, 2001). For example, metal competition (e.g. Ca^{2+}) or complexation of carbonates can potentially reduce stable elements bioavailability, accumulation and bioconcentration in aquatic system (Pascoe et al., 1986; Spry and Wiener, 1991; Muscatello and Janz, 2009). Co, Mo, Se and Sb released into aquatic environment may be removed by plankton which are primary producers and later deposited on sediments or

dead organic materials (Muscatello and Janz, 2009). Macroalgae as primary producers has been linked as a source of essential trace and stable elements and are important bioindicators of stable elements pollution (Kalesh and Nair, 2006) and should likely accumulate high number of stable elements however, results from this study contrast this. Results from this study showed that CRs values from Sb, Mo, Co were 2-3 order of magnitude lower than values reported in IAEA. Variation between the element increases in the order (Sb< Mo< Co) with highest concentration obtained in cobalt. These differences may be attributed to metal ions, ambient solution or nature of macroalgae itself (Eisler, 2009).

3.5.2. Discussion of results for the food chain

Much of human foods are directly or indirectly linked to plant materials. Plants and vegetations including the human food chain may be subject to direct or indirect contamination following atmospheric releases of radionuclides. Contamination by radionuclide of the food chain may lead to high human exposure to radionuclides and as such detailed study of radionuclides transfer in the SSA would improve knowledge of radionuclide contamination to human food chain, assess impact and prevent human radiological exposure as well as guide future researches and modelling radionuclides transfer in SSA. Results have shown that there are variations in CRs values of stable elements for cereal, legume, root, tuber, leafy vegetables, maize and vegetables. These variations may be a result of several factors including crop morphology and physiology for stable elements, soil, radionuclides/ stable element, climate and time factor (Golmakini et al.,2008; IAEA, 2010). Past literatures reported that different part of plants show varying ability for uptake and accumulation of stable elements (Kabata pendias, 1995; Wang et al., 2013). In another study by Smical et al. (2008), demonstrated that CRs values vary in order of leafy vegetable>vegetable>root> cereals. Another report found the mean concentration of heavy metals in cereal was lower compared to leafy and non-leafy vegetables (Sinha et al., 2006; Singh et al.,2010). For this study, higher concentration for cereal have been observed in Co, Ni and Pb which is 1-2 order of magnitude higher than IAEA, however, for Mn and Zn, IAEA CRs values were 1 order of magnitude higher than SSAD. The variation in CRs values may likely be attributed to some of these factors already mentioned in chapter two of this study and which include the biochemical behaviour of individual elements, soil mineralogical composition, organic matter, pH and fertility (IAEA, 2010). The soil (media) where the plant grows influences the uptake of

radionuclide. The concentration of this elements depends on soil moisture, the pH, CEC, OM content, microbial activities, soil structure, clay mineral content and agricultural practices (IAEA,2010). CRs values in tropical and sub-tropical soil which are high in acidity and majorly 1:1 clay mineral may affect the uptake and accumulation of stable elements (Fan et al., 2014). Most soils in SSA are regularly cultivated for agricultural purposes and cultural practices of ploughing are practices which disturb the vertical distribution of radionuclides. This mixing (ploughing) enhances contact between deposited particles and soil matrix which will results in dilution of radionuclides concentrations and increased sorption (Strebl et al., 2007). Similarly, fertilizers such as NPK are routinely applied to maintain adequate crop yield and productivity which in return boost nutrient deficiency and low pH Both low pH (acidic pH) and poor nutrient status reduces crop yield and promote high radionuclide uptake. Poorly drained and organic soils increase radionuclide transfer (Strebl et al., 2007).

The CRs of strontium was observed to be higher in tuber, legumes and vegetable except for leafy vegetable where lower value was obtained compared to IAEA. The CRs values were in the same order of magnitude except for tuber where SSAD was one order of magnitude greater than IAEA. The highest Sr CRs was observed in legumes and it follows in the order (Legumes > vegetables> leafy vegetables>tuber). However, the SSAD CRs were limited by fewer replicates compare to IAEA except for leafy vegetables where higher replication was observed. Sr CRs were 2 order of magnitude higher compared to Cs CRs for tuber crops. Sr and Cs are chemical analogues of Ca and K respectively. The influence of elemental analogues may affect accumulation and transfer Sr and Cs in tuber (Baeza et al.,1999; IAEA, 2010). The uptake and metabolism of strontium follow a trend like that of calcium (Coughtrey and thorne, 1983; Golmakani et al., 2008). Strontium to calcium ratio was observed to be highest in root crops, followed by cereals and then fruits. Strontium uptake is therefore inversely related to the amount of exchangeable calcium in the soil. The greater the exchangeable calcium the lower the Sr/Ca ratio and the lower the uptake of strontium (Golmakani et al., 2008).

Uranium was observed to be high in vegetables and one order of magnitude higher than IAEA. High transfer of radionuclides has been associated with vegetables from previous studies (Khan et al., 2011). However, variability is not an uncommon phenomenon in CRs values which may likely be influenced by the soil types and other variables (such as plant, chemical nature

of radionuclides, soil organic matter, pH, fertilizer application) (IAEA, 2010). Uranium in plant is greatly influenced by the uranium content in soil at such granitic weathering soils produced the uranium richest vegetable and forage crops (Muller et al., 2010). According to Muller et al. (2010), high amount of uranium was observed with vegetables, green folders, grasses, legumes, spices and herbs but lower concentration of uranium in starchy food stuffs (honey, cereal, wheat, rye, bread, margarine, seeds). The accumulation of uranium decreases with aging of plant due to dilution effects by other assimilates in the plant (Muller et al., 2010) and the aging effects is commonly observed with macro as well as trace elements.

3.6. Conclusion

A Sub-Saharan African database of radionuclides transfer parameters has been developed. The database has been developed from CRs data compiled from about 211 articles obtained from the comprehensive review of journal articles from Sub-Saharan Africa (SSA). Concentration ratios (CRs) which consists of CRs values for wildlife (terrestrial and aquatic), as well as human food chain from SSA has been presented. The CRs cover a range of radionuclides and stable elements as well as food crops and wildlife. The results showed that concentration ratio typically conform to a lognormal distribution. The results suggested that SSA CRs were different from those of IAEA. There was no consistent pattern observed in the CRs for SSAD and IAEA.

Comparison of SSAD and IAEA CRs was undertaken for radionuclides and stable elements in different wildlife groups and food crops. While significant differences have been observed in some radionuclides-organism combinations, in some other organisms no significant differences have been observed. In food crops, strontium has been observed to show significant difference in root and tuber crops but no significant difference with vegetables and direct opposite relationship being observed with uranium being significant with vegetables and no significant difference for root and tuber crops. For food crops, the mean concentration ratios were higher in SSAD compared to the IAEA. The result agreed with Velasco et al. (2009) which suggested that there is a difference in transfer factors for tropical or subtropical environments compared to transfer factors from the temperate environment. Variability observed in transfer factor may be attributed to a combination factors already highlighted chapter 2.

4. RADIONUCLIDES TRANSFER TO FOOD CROPS AND ICRP REFERENCE ANIMALS AND PLANTS (RAPS) AT PROPOSED NUCLEAR SITES IN NIGERIA

4.1. Abstract

Reviews of radionuclides environmental impact assessment and transfer to human food chain started many decades ago (Brechignac, 2001; IAEA, 2009). As a result, dynamic food chain models and computer codes known as PATHWAY (Whicker and Kirchner, 1987), COMIDA (Abbott and Rood, 1994), FARMLAND (Brown and Simmond, 1995), were developed to assess the environmental impacts of radionuclide transfer to human food chains. Similarly, but most recently, a system for radiological environmental protection of non-human biota (wildlife) based on the use of Reference Animals and Plants (RAPs) has been developed. The International Commission on Radiological Protection (ICRP), recommended a set of Reference Animals and Plants (RAPs) based on which environmental assessment for non-human biota can be made (ICRP, 2007). This study presents the results of the assessment of radionuclides transfer to human food crops and ICRP Reference Animals and Plants (RAPs) in Sub-Saharan Africa. It is the first research study on ICRP RAPs in the Sub-Saharan Africa.

Samples were collected within 0.4km^2 area of the two planned locations (Geregu and Itu) for nuclear power build, in Nigeria. This study determined the concentration of nine stable elements which include Caesium (Cs), Strontium (Sr), Cobalt (Co), Selenium (Se), Uranium(U), Thorium (Th), Molybdenum (Mo), Europium(Eu) & Cerium(Ce) and the corresponding whole-body (non-human biota) concentration Ratios (CRs). Concentration ratios were determined for five terrestrial RAPs and six agricultural food crops as well as the corresponding concentrations in soil samples to both human food crops and non-human biota samples (wildlife). The agricultural food crops sampled include (cassava, maize, rice, plantain, okra, groundnut(peanut)), and terrestrial RAPs include (rat, frog, bee, earthworm and wild grass). Agricultural food crops and RAPs were collected from both locations in Nigeria. Concentration of stable elements radionuclides analogues were determined for both agricultural food crops and RAPs using Perkin Elmer Microwave Plasma Atomic Emission Spectroscopy (MP-AES).

Results of the stable element analysis showed that the concentration of stable element in the Sub-Saharan Africa (SSA) are significantly higher for both agricultural food crops, wild grass

and small mammals compared to concentration reported in the IAEA publication. Amphibians, annelids and arthropods present lower activity concentration values compared to IAEA data. Subsequently, Concentration Ratios (CRs) of the elements in both food crops and wildlife were estimated. The results were statistically compared with values presented in the IAEA (2009) and a significant difference were detected between CRs values obtained from Sub-Saharan Africa (SSA) and the those in the IAEA publication. Higher concentration ratios observed in the SSA data may be attributed to several factors already highlighted in chapter two of this study and which may include soil properties and climatic conditions.

4.2. Introduction

Several extensive studies on radionuclides transfer along the food chain have been undertaken. Earlier research studies focused on the evaluation of the biological impact of nuclear weapons testing and releases especially from military cantonments. During the early studies on global radionuclides fallout on man, some mobile radionuclides (^{90}Sr, ^{137}Cs and ^{131}I) accumulated in human food stuffs in the environment (Brechignac,2001; IAEA,2009). In the 1960s, the list of these radionuclides expanded with the development of civilian uses of nuclear energy and further experiment on transfer of activation products (^{54} Mn, ^{60}Co, ^{65}Zn), natural radionuclides (^{238}U, ^{226}Ra, ^{232}Th, ^{210}Pb, ^{210}Po), transuranic (^{237}Np ^{240}Pu, ^{241}Am) and other radionuclides (^{3}H, ^{14}C). The scientific basis for predicting contamination to agricultural food and various other contamination assessment studies and model developments started to develop (IUR, 2001). In Europe and North America, wide research on radionuclides transfer have been undertaken and assessment approaches/models to simulate the transfer of radionuclides through terrestrial foodstuff have been developed (including FARMLAND- Food Activity from Radionuclide Movement on LAND, ECOSYS-87 (Matthies et al., 1982; Kohler et al., 1991), the Absalom approach) (Brown and Simmonds, 1995; Absalom et al., 1999). Most of these models/approaches have been used to assess radionuclide transfer through the food chain in Europe, particularly after the Chernobyl nuclear accident (Kohler et al., 1991). Technical documents, transfer parameter handbooks and compilations which provide requirements for quantifying transfer to foodstuffs, cereals, vegetables, pastures and grasses are available (IUR, 1989; IAEA, 2009).

The protection of the non-human biota started about two decades ago because of the consideration that environmental must be total and the protection of man does not guarantee other components of the ecosystem are adequately protected (Pentreath, 2007). Since then, environmental protection has evolved through different stages due to increasing concerns on the need for humans and wildlife to be protected from anthropogenic radiation sources. Several concepts have been suggested including the concept of "Reference Man" (Pentreath, 2007,2009), the suggestion of assessing the environment on its own'' (ICRP,1991; ICRP,2007; ICRP, 2008) and the concept of Reference Animals and Plants (ICRP, 2007,2008). Based on the ICRP recommendation, this study conducted a research sampling in Nigeria, focusing on and carefully aligning sampled organisms to the terrestrial ICRP RAPs.

Nuclear programmes have started to develop in Sub-Saharan Africa and Nigeria, South Africa, Kenya, Niger and Ghana have plans to construct nuclear power plants. Nigeria has planned to improve its electricity generation through the introduction nuclear energy to increase its energy mix (http://www.world-nuclear-news.org/NN-Agreements-signed-for-Nigerian-nuclear-project-3110177.aspx). The country planned to achieve 1000MW capacity with Nuclear Power Plants in the first year of installation and is expected to increase to 4000/5000MW by 2030 (Aduba, 2012; Aliyu et al., 2015). There could be potential release of radionuclides when the planned nuclear plant become operational. The country has identified two locations for the proposed nuclear plants. These locations, Geregu and Itu have been selected as case study sites for the collection of soil, plant and biota samples.

In the event of planned discharges of radionuclides, assessment by means of transfer models which estimate transfer through compartments (food chain) of the environment is critical (IAEA, 2001). Models can be applied to assess the impact of accidental releases of radionuclides and to predict future impact of releases from underground repositories (IAEA,2010). However, model reliability depends on data quality and measurements made in the environment being assessed (IAEA,2010). As a result, it is important to develop transfer parameters data for the region which can be used as input to quantify transfer and to conduct an environmental impact assessment.

The development of nuclear programmes in Sub-Saharan Africa and planned nuclear power plant construction in Geregu and Itu suggest, there is a need to estimate radiation doses that

humans and non-human biota would receive as a result of the nuclear facility either by routine or accidental discharges. This study will attempt to assess the radiological effects of the planned nuclear plant on humans and non-human biota. The Environmental Risks from Ionising Contaminants: Assessment and Management (ERICA) integrated approach would be used to assess the risk impact due to ionising radiation on non-human biota.

Models have been developed for assessing radionuclide transfer to wildlife. This include the ERICA Tool (Brown et al., 2008), RESRAD-BIOTA (USDoE, 2003), R&D 128/sp1a (Copplestone et al., 2001, 2003). These models require inputs to quantify exposures (especially dose rate) of wildlife to radiation effects (Vives i Battle et al., 2007; Beresford et al., 2008a). Many of the model used the concentration ratio to estimate activity concentration in the organisms and consequently their internal dose rates (Copplestone et al, 2001, 2003). The modelling approach represents transfer of radionuclides to wildlife by simple Concentration Ratios (CRs), which allow prediction of whole organism activity concentrations from activity concentrations in environmental media (soil, water or air) (Beresford et al., 2008a; Beresford et al., 2008b; Beresford et al., 2008c; Copplestone et al., 2001; Hosseini et al., 2008; USDOE, 2003). Refer to section 2.5 of this study for more information on the concept of concentration ratio modelling approach.

About 200 elements /RAPs combination were reported in ICRP publication, ICRP, (2009), but data is sparse and only a few (about 37%) elements/ RAPs has data available in the wildlife transfer database (http://www.wildlifetransferdatabase.org) and for some radiological significant elements (like iodine) data are not available (Copplestone et al., 2013; Guillen et al., 2018). The table 5.1 shows the terrestrial RAPs and the specific family defined in the RAPs.

Table 4.2. Terrestrial Reference Animals & Plants (RAPs) (ICRP, 2008)

Terrestrial RAPs	**RAPs Sample**	**Family**	**Species sampled**
Deer	Not sampled	Cervidae	Nil
Rat	African rat	Muridae	*Arvicantis niloticus*
Frog	African Frog	Ranidae	*Amnirana galamensis*
Duck	Not sampled	Anatidae	Nil
Bee	Honeybee	Apidae	*Apis mellifera*
Earthworm	Earthworm	Lumbricidae	*Lumbricus terrestris*
Pine tree	Not sampled	Pinaceae	Nil
Wild grass	Guinea grass	Poaceae	*Panicum maximum*

Both the ICRP RAPs and ERICA approaches have been used for conducting environmental assessments (ICRP, 2007; Larsson, 2008; Aliyu et al., 2015). Aliyu et al. (2015), has used the ERICA approach to assess the risk of the proposed nuclear plant by using ERICA generic data. While RAPs form the basis for collating and analysing data useful for environmental impact assessment, it also provides advice for wildlife and environmental protection (ICRP, 2008). The ERICA encompassed a broader wildlife groups, defined in less specific family level unlike the RAPs (ICRP., 2008). According to ICRP (2009), data for radionuclide transfer assessment can be collected once a suitable site has been identified. Sampling of five RAPs and six food crops in July 2017 at two proposed sites for nuclear build, Geregu and Itu in Nigeria were undertaken.

Radionuclides have different sources and pathways through which they are transferred and contaminate the food chain in the terrestrial ecosystem (Muller and Prohl, 1993). Basically, major pathways include atmospheric dispersion, groundwater dispersion, inhalation, root uptake, foliar deposition, ingestion, (Muller and Prohl, 1993).

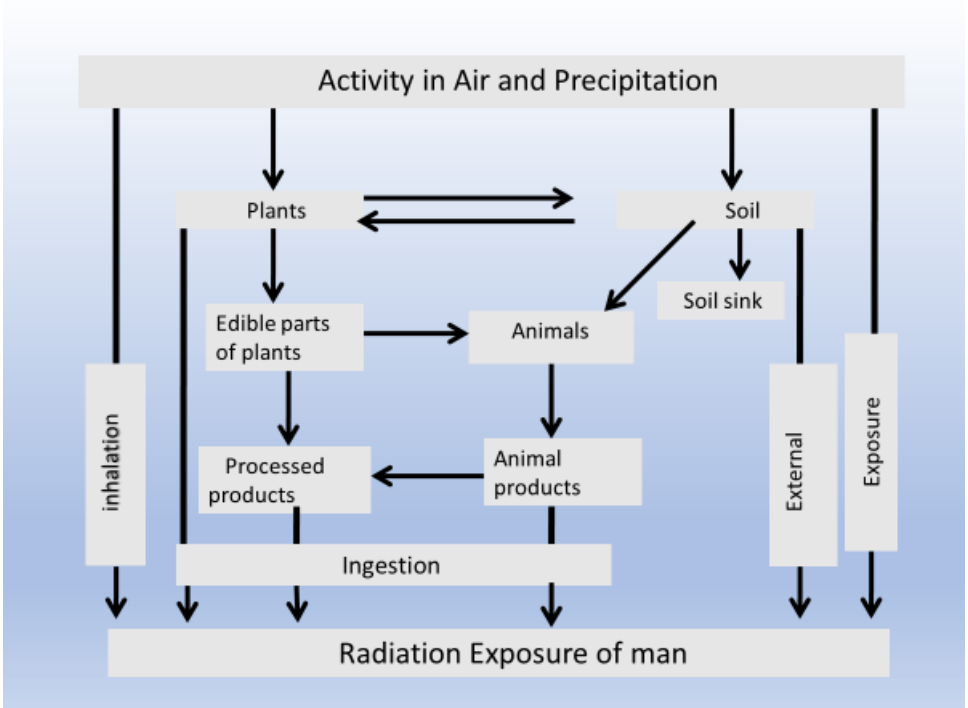

Figure 4.2. The pathways of radionuclide transfer in terrestrial ecosystem (Muller and Prohl, 1993).

4.3. Materials and Methods

4.3.1. Sampling sites description

Two case study sites, Geregu and Itu are both located in Nigeria, guinea savannah and rain forest vegetation zones respectively. Brief description of both sites is highlighted below.

Geregu is located on approximately latitude 7.56 N and longitude 6.69E to the north of Nigeria (Chad-Umoren, 2013). The location's climate is diverse and characterised by natural grassland, sparse woodlands with long growth periods (Jagtap, 1995; Clayton, 1961). The major soil in the location include nitisol, fluvisol, lixisol, ferralsol with coarse texture, low in organic matter and nutrient fertility content (Kolawole, 2003). Sampling campaign covers an approximate area of 0.4km^{2}and to the south of the sampling site is the flood plain which extends into the Geregu river while towards the north lies mountainous highlands with shrubby vegetation (Clayton, 1961). The annual rainfall is approximately 1123mm and the mean monthly maximum and minimum temperatures are 32^{o}C and 22^{o}C respectively in wet season and little fluctuations experienced during the dry season to between 35-40^{o}C (Jagtap, 1995). The inhabitants were mainly farmers and staple food crops like rice, maize, groundnut,

cassava, yam, melon, plantain, okra was locally cultivated and consumed. Figure 4.1a shows map of sampling locations in Geregu.

Figure 4.1a. Map of Sampling Locations in Geregu in relation to Nigeria and SSA

The map 4.1a legends were used to represents food crops and wildlife sampled from the location and these codes include CS= Cassava, OK= Okra, GN=Groundnut, FG=Frog, GR=Grass, BE=Bee, RT=Rat, MZ=Maize, RC=Rice, PT=Plantain, ET=Earthworm. The map in figure 4.1b sampling points of the second case study location

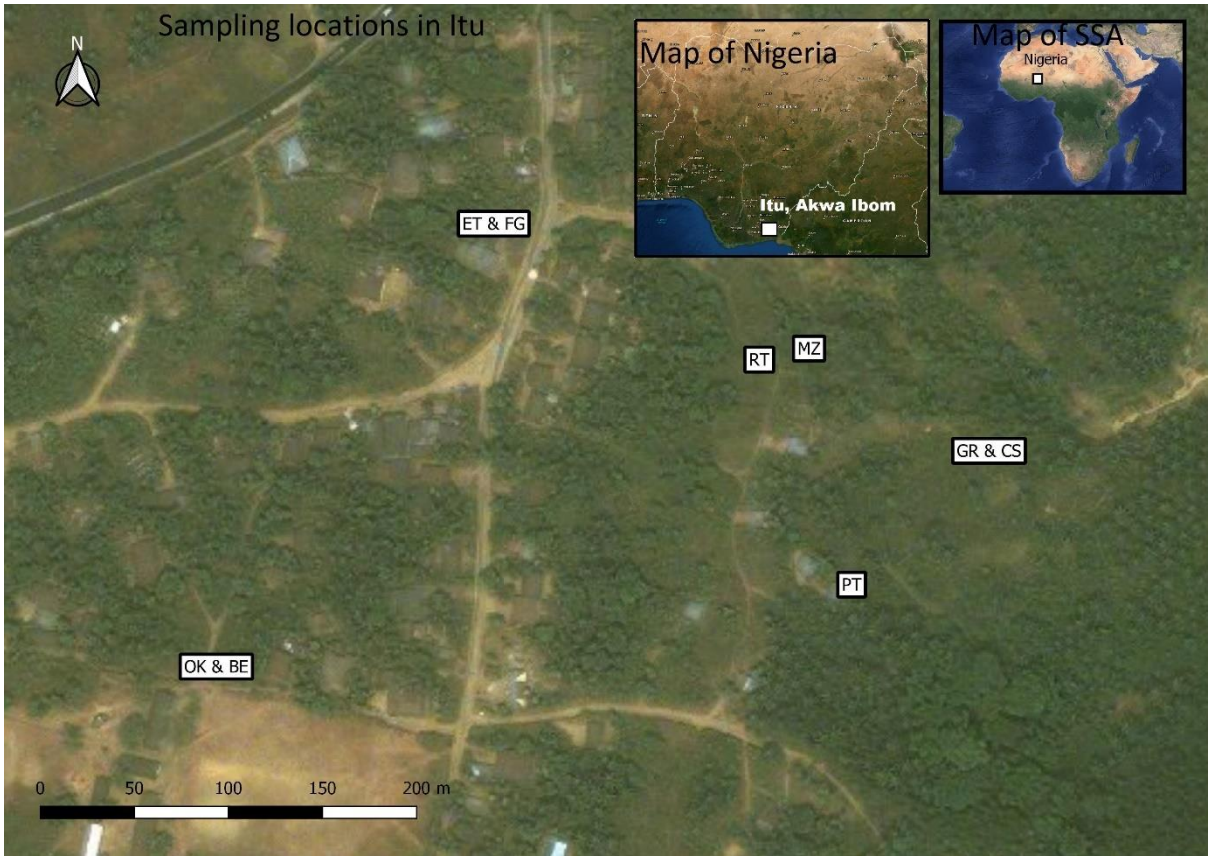

Figure 4.1b. Map of Itu sampling locations in relation to Nigeria and SSA (see maps legends explained in figure 4.1a)

The second case study location Itu, in Akwa-Ibom State, Nigeria s located on approximately, latitude 5.12N and longitude 7.59E and it is part of the rain forest vegetation zone characterised by estuaries, creeks, rivers, mangrove with heavy rainfall (Ajibesin et al., 2008). Rainfall is about 1500-2000mm during the wet season and the vegetation is typically of tall trees (including the Iroko, mahogany, oil palm, rubber tree, obeche). Food crops such as cassava (Manihot esculenta), maize (*Zea mays*), okra (*Abelmoschus esculenta*), banana (*Musa balbisiana),* cocoyam (*Colocasia esculenta*) and palm oil (*Elaeis guineensis*) are commonly cultivated. Wildlife found in the location includes monkeys (*Macaca fascicularis*), antelopes (*Antilocapra amaericana)*, warthogs (*Phacochoerus africanus*), snails (*Achatina fulica*), grasscutters (*Thryonomys swinderianus*), squirrels (Sciurus vulgaris), rats (*Cricetomys gambianus*) and rabbits (*Poelagus marjorita*). There are different kinds of domesticated animal ranging from cattle (including the White Fulani, Red Bororo, Muturu, Sokoto gudali, Ndama and Kuri), goat (include West African dwarf, Red Sokoto), sheep (include Balami, Uda and Yankasa), poultry (include the breed of Rhode Island red, (Blench et al., 1995). The

commonly practiced system of animal production is the free-range grazing to semi-intensive system.

4.3.2. Justification for selected sites.

The justifications of these locations for the research case study include;

(1) Planned construction of nuclear power plant

(2) Selected food crops and wildlife are available in this location and widely consumed by the people

(3) To provide site specific concentration of radionuclides/ stable elements (Sr, Se, Co, Mo, U, Th, Eu, Ce, Cs) and CRs for human food crops and wildlife.

(4) To ensure site specific data are available for emergency preparedness, response and future environmental planning

(5) To provide an opportunity to develop transfer parameter data for ICRP reference animals and plants (RAPs)

(6) To enable dose assessment of the potential impact of the nuclear reactor on wildlife within the a SSA setting using ERICA Tool

(7) To obtain data which will serve as benchmark for conducting radiological impact assessment for Sub-Saharan Africa

4.3.3 Food crops sampled

Conducting a study on radionuclide transfer to human food chain, it is important to consider major agricultural food crops in the region and thus, research campaign focused on six principal staple food crops: cassava (*Manihot esculenta*), maize (*Zea mays*), rice (*Oryza sativa*), okra *(Abelmoschus esculenta*), groundnut (*Arachis hypogea*) and plantain (*Musa paradisiaca*). The average per capita daily calorie intake in Nigeria increase from 2050 kcal to 2700 kcal between 1981-2002 and cereals, root and tuber percentage in the diet increases from 64-65.3% during this period (Agboola et al., 2004; FAO, 2004). Sample collection aimed at the edible part(s) of the crop which includes tuber (cassava), grains (maize & rice), green seed pod (okra), fruit (plantain) and pod or seed (groundnut). Sampling was undertaken directly from farmland and samples were washed, cleaned and kept in a sealable polyethylene bags clearly labelled to identify the sample.

Manihot esculenta (cassava) is a major food crop that is primarily cultivated and consumed for its edible root (carbohydrate), leaves and shoot are relatively high in protein (FAO, 2008). Over 200 million people in the region obtain more than half of their calories from foods made from cassava roots (Manyong, Dixon et al. 2000). Currently, Nigeria is the largest producer of cassava in the world with an estimated production of 46 million tonnes in 2007 and the second largest consumer in SSA after democratic republic of Congo (FAO,2013). Cassava was sampled by first cutting the stem and pulling the lower proportion of the stem to uproot the tubers. The tubers were dislodged from the plant by cutting and kept in the sampling bag. Some cassava plants depending on their viability produced more than one root tuber and where this occurred all tubers were retained for analyses.

Zea mays (maize) is an annual fast-growing staple food crop that can tolerate different climatic conditions and grow well in a broad range of soil types. Maize is commonly cultivated and consumed across the sub-Saharan area (www.pfaf.org/maize). It can be processed into starch, consumed fresh, boiled or roasted (www.pfaf.org/maize) Maize contains some essential vitamins like vitamin A, B1(Thiamine), B2 (Riboflavin), B3 (Niacin), C and vitamin E as well as calcium, potassium (low), iron, phosphorus, magnesium, manganese, zinc, copper and selenium(high) (Edema et al., 2005). Sampling of maize involves laying out the plots and cutting the maize cob from the plant stalk. The husk was then removed, and the cob placed in the polyethene sampling bags. More than one maize cob was harvested from some plants. Five samples of maize were collected from each location (Geregu and Itu).

Musa paradisiaca (plantain or cooking banana) is an herbaceous crop. It grows up to about 9m and produces fruits which are highly consumed in West Africa. Fruits are oblong, fleshy, 5-7cm long(wild) and even longer with cultivated varieties (Imam and Akter, 2011). Medicinally, the plant is useful for treating some diseases such diarrhoea, diabetes, anaemia, hypertension and cardiac diseases. Green fruits of *Musa paradisiaca* have been known to have hypoglycaemic effects. Sampling involved cutting or two fruits from the plantain bunch while it was hanging on the plant. In some instances, the plant stem was cut, and the fruit bunch removed. Only one finger was removed and placed in the sampling bag.

Arachis hypogea (groundnut or peanut) is an annual crop, growing to 0.3m, in a light to medium or heavy clay soils but does well in well drained loamy. In most cases it is cultivated

in seed beds and can tolerate high pH range (4.3-8.7). The plant prefers hot dry conditions and is widespread in Sub-Saharan Africa and commonly consumed boiled, roasted or dried or processed into other products (www.pfaf.org/uer/plant.aspx?lat). Groundnuts were sampled by grabbing and pulling the plant from the loose soil (the seed pods develop underground) and the pods were carefully removed and placed in sampling bags. Several pods were harvested from a stand depending on viability.

Oryza sativa. (Rice) is an important food crop in the Sub-Saharan Africa. The demand for rice consumption is so high that local production is unable to meet increasing demand (FAO, 2006a, Hossain, 2006). Rice production is widely distributed in SSA, being cultivated in 38 countries covering an 8.46 million ha with Nigeria and Madagascar taking the lead (FAO,2006a). Wetlands and swampy conditions are the most suited areas for rice cultivation (Andriesse, 1991) and these location makes rice vulnerable to contaminations from the environment and to the influence of variability in abiotic stressor including temperature, drought, flood, rainfall, salinity, acidity and alkalinity (Balasubramanian et al., 2007; Pandey and Bhandari, 2008). Rice was sampled by cutting and harvesting the grains. A uniform sampling approach described by Alloway. (2013) and (ISO,2002), was adopted as shown in figure 4.3c.

Abelmoschus esculentus (Okra) is primarily cultivated for its fresh pods and leaves which are consumed fresh in most SSA countries. According to FAO/WHO, 2003 fruits and vegetable consumption have played a critical role in improving the health of the people. The distribution of okra traverses the agro-climatic region of SSA (Adeniji and Aremu, 2007). The fibre and mucilage used as moisture absorber and for the synthesis of biodegradable polymers (Maria de rosa et al., 2010). The okra pod was harvested by cutting with a knife from the stalk with one or more fruits being harvested from some plants. The samples were placed in polyethylene sampling bags and taken to the laboratory for preparation. In Geregu and Itu, at least five samples each of the food crops were collected.

4.3.4. RAPs sampled

Five RAPs were collected and below is a small note describing how each RAPs were collected

- Rats (*Arvicanthis niloticus*). is traditionally known as the African grass rat that is found along the Nile river and in many Sub-Saharan African countries. It belongs to the family

muridae and has many species. *A. niloticu*s are herbivores and feed on grasses, leaves, stems of flowering plants, seeds, cultivated crops and arthropods. *A. niloticus* are medium sized rats with stoutest bodies (average body mass and length of 118g and 130mm respectively). it is a gregarious species that lives in underground burrows, around wood stumps and sheds (https://animaldiversity.org/accounts/arvicanthis_niloticus)

A total of 5 small rats in the family of muridae were sampled from the two case study locations. At the time sampling was carried out in July, rat in the region have started to hibernate and were difficult to capture. Humane method involving metal traps were used for the catching. Traps were placed in locations where signs of animal faeces, burrows or grazing path of animals were noticed, as well as spots where cassava peelings or maize cobs were locally pre-processed on the farm (e.g. cassava peel dumps). Traps setting were done in the evenings and baits including smelling fish, bread, maize, oats were used in the setting of the rat cages. Inspection for a possible catch and swapping and changing of baits were done the following morning (Yankovich et al., 2013; Barnett et al., 2014).

- Frogs (*Amnirana galamensis*), *A. galamensis* belongs to the family Ranidae and is well-adapted and distributed across the Sub-Saharan Africa. About seven other species exist and may be found in Africa. *A. galamensis* is a plump frog measuring between 62-77.4mm(length) with typical colour patterns (drab pale brown to dark brown) and broad flat dorsolateral ridges. In the dry seasons' species are found along riverbanks and during the wet season they are found around pounds, grassland and forest in the savanna (Jongsma et al., 2018; amphibiaweb.org/species/5036)

  Eighteen adult frogs were collected in both case study sites. Frogs were captured after a heavy rainfall by using a plastic bottle traps suspended in a pool of water and in some places, they are buried in the ground close to river shore locations. Usually, after heavy rainfall episodes, the frogs start to explore in the pool of water and in the process get trapped in the plastic traps (Wood et al., 2008).

- *Apis mellifera* (Honeybee) Belong to the ICRP Reference Apidae. Its widespread in Sub-Saharan Africa and some other parts of the world (Europe, Asia) (Al-Ghamdi, Nuru et

al. 2013). Broad diversity of 16 subspecies exist (Shaibi, Fuchs et al. 2009). Morphologically, species are distinct in body size, hair length and colour (Al-Ghamdi, Nuru et al. 2013). Differences in bee phenology have been identified in their reproductive swarming, migration and temperament (Al-Ghamdi, Nuru et al. 2013). Economic importance of bee includes production of honey by beekeepers, a major occupation in locations where they are found.

A. mellifera were collected using a bee bowl (30cm diameter plastic bowl). Different colours of bowl (white and blue coloured bowls) half filled with water were used. Some were placed on the ground while others on elevated wooden stumps close to flowers of similar colours and covered with wire gauge (Barnett et al., 2014). During sampling campaign, the weather condition was bright and sunny for most times except for a few occasional showers at some points. At Geregu, bee traps were emptied 2-3 days and all bees were sieved out. The fresh mass of individual bee was recorded alongside with their length and breadth. Thirty randomly selected individual bees were bulked to form one bee sample. A combination of the bowl sampling and bee hunting was used at Itu. In this approach, with our body properly covered, we attacked the beehive with fire, and bees were harvested.

- Earthworm *(Lumbricus terrestris*). This species belongs to the ICRP RAPs family, lumbricidae, and are broadly distributed throughout the Sub-Saharan Africa (Daniel et al 1992, Schutte et al, 2010). L. terrestris were collected by digging with a hoe to a depth of 10-15cm in suspected locations where earthworm cast were found. These locations were very humid areas with earthworm excrement (Barnett et al., 2014). Earthworms were excavated alongside ball of earth and this was washed off with water. Fifteen individual earthworms were collected and composited into one sample. Five samples each were collected from Geregu and Itu location.

- Wild grass (*Panicum maximum*). Also referred to as guinea grass, belongs to the family poaceae which the ICRP reference wild grass belongs and are widely distributed in the Sub-Saharan Africa. They share similar characteristics with the reference wild grass and are everywhere in the two identified case study locations. Five samples each of Panicum maximum were collected from each sample location by cutting using a knife and cutlass and collected samples well-kept in labelled polyethylene bags.

4.3.5. Soil sampling

Soil samples were collected at the same locations food crops and wildlife were collected. Sampling depth of 0-10cm was considered for RAPs based on IAEA recommendations (IAEA, 2010; Barnett et al., 2014). For food crops sampling depth of 20cm were considered being the standardized rooting depth recommended by International Union of Radio ecologist (IUR) (IUR,1989; IAEA,2010). A soil auger was used for collecting soil samples and three soil cores were collected, thoroughly mixed to provide a representative sample. Soil were kept in a sealable polyethene bag and taken to the lab, where soils were air dried until they attained a constant weight. Wood fragments, if present, were removed by hand and the soil then sieved (2mm) and both fresh and dry (25 ^{0}C room temperature) masses of the samples determined. Figure 4.3c shows the sampling layout for the research campaign.

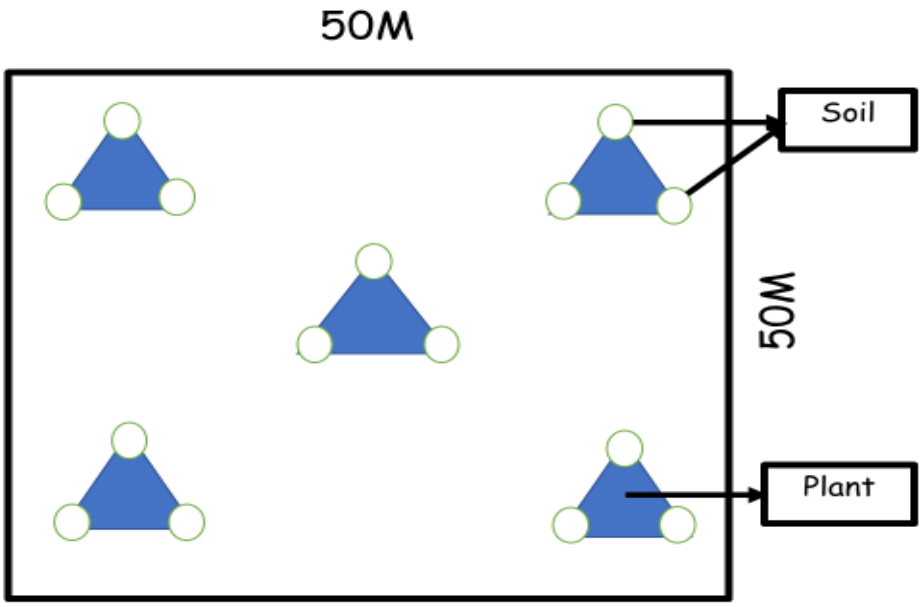

Figure 4.3c. Farmland sampling layout (ISO, 2002a; ISO,2002b; Alloway, 2013). The dark inner triangular legend represents wildlife/food crop sample and the 3 outer white coloured of the legend connotes soil sampling points.

4.4. Sample preparation

4.4.1. Soil and crop sample preparation

The plant and soil samples were taken to the laboratory and the fresh mass recorded. The soil samples were placed on top of newspapers and air dried for 3-5 days at room temperature (25^0C) in the laboratory until they attained constant weight. Plant samples were washed with distilled water, cleaned, chopped into small pieces. Cassava and plantain were peeled before washing with deionised water. Thereafter, samples were packed in a labelled brown paper envelope and placed in the oven for drying at a temperature between 65-70^0C until constant mass was obtained and the dry mass determined. The determined samples were ground into a fine powder in the laboratory (Kogi state University and University of Uyo soil science Laboratories). The samples were sieved through a 2mm sieve and packed in labelled sealable polyethylene bags, ready for MP-AES analysis (Varbanova and Stefanova,2015).

4.4.2. Wildlife sample preparation

- The rats were killed by dislocating the neck (Home Office, 2013). Rat species was identified, and the fresh mass, length, width and height was measured and recorded. The rat skin and gut content were carefully removed in the laboratory (Wood et al., 2008). The whole body was kept in brown envelopes and oven dried to a constant weight.

- Frogs were killed by striking the cranium, cutting through the spine at the base of the skull and inserting a needle into the brain cavity to permanently destroy the brain (Home Office, 2013). The gut contents were removed and discarded to ensure no contamination of the whole-body measurement by gut content. (Wood et al., 2008).

- The earthworm samples collected were placed in an aerated container with damp tissue paper to allow for gut evacuation (Barnett et al., 2014). The specie was identified, and fresh mass, length and breadth was measured and recorded. The earthworm was then kept in the fridge at low temperature (4^0C) and pressure to allow for dehydration (Yankovich et al., 2013).

- The bees and the wild grass were both placed in the brown envelope and oven dried to a constant weight respectively. All wildlife samples were ground using a mortal and sieved through 2mm sieve and packaged in a sealable bag for analysis

The MP-AES uses microwave excited plasma source that runs on air and nitrogen. It has improved performance, superior detection limits, improved dynamic range, higher sample throughput and twice faster than the conventional flame AAS (Vysetti et al., 2014; Karlsson et al., 2015). The nitrogen gas gives the robust plasma a conventional torch and the microwave magnetically excites the nitrogen plasma. The magnetic excitation provides a robust high temperature, and a central channel suitable for sample atomization. It then creates high intensity atomization emission lines, which then enable superior detection of a range of metals and non-metals (Varbanova and Stefanovic, 2015).

4.5. Laboratory analysis

4.5.1. Soil digestion

Perchloric acid digestion method (Adler and Wilcox,1985, 2008) was used for the digestion of soil samples before elemental analysis. Two grams of soils was weighed into 300ml conical flask and 30ml of 72% $HClO_4$ (perchloric acid) was added. The conical flask was placed on a hot plate and commenced digestion at 130^{o}C in a fume cupboard. Digestion took about 40 minutes until the solution appeared colourless and white fumes of $HClO_4$ appeared. Flask was removed and allowed to cool. Fifty millilitres of distilled water were added, and the solution was filtered through a Whatman filter paper into 250ml volumetric flask. The emerging filtrate was poured into plastic bottles for elemental analysis by Microwave Plasma Atomic Emission Spectroscopy (MP-AES).

4.5.2. Soil analysis

The soil analyses conducted included soil particle size analysis, soil pH, organic matter, cation-exchange capacity, available phosphorus, exchangeable acidity, organic carbon and nitrogen content. The soil Cation Exchange Capacity (CEC) was determined by the summation of the exchangeable bases including K, Ca, Mg, Na, and exchangeable acidity (H^{+}). The total elemental analysis was undertaken using MP-AES. There were two research locations, five wildlife samples and six food crops samples and a minimum of six research areas sampled in each research location and 110 total number of soil samples.

4.5.2.1. Soil particle size

Particle size using the USDA classification divide soil into three major size classifications: Sand (2.0-0.05mm), silt (0.05-0.002mm) and clay (0.002mm) (Gee and Bauder, 1986). The soil textural composition is a marker to soil water retention, leaching and erosion potential, plant nutrient bioavailability, mobility and transfer, OM dynamics and carbon sequestration capability (Kettler et al., 2001). Particle size can be used to assess soil quality and sustainability of cultural and agricultural practices. Soil particle size can be determined by a few methods including rapid method and standard hydrometer techniques (Cambardella et al., 2001; Kettler et al., 2001). However, the Bouyoucos hydrometer method was adopted to determine the particle size (Udo & Ogunwale, 1986; Gee and Bauder, 1986).

4.5.2.2. Procedures for the standard hydrometer (Bouyoucos) method

The apparatus used included 1 litre glass cylinder, hydrometer, thermometer and a mechanical shaker (multi mix machine). The reagents used included sodium hexa-metaphosphate and 7g of sodium carbonate (anhydrous) weighed into 500ml of distilled water. The solution was stirred and made up to 1 litre and then filtered. Fifty grams of 2mm sieved oven dried soil sample was weighed and placed in the multi-mix baffled cup and then filled with distilled water half-full and 50ml of Sodium hexa-metaphosphate (reagent) solution was added. The baffled cup was placed on the mechanical stirrer and stirred for 10min until the soil aggregates were broken down. The suspension was transferred into the Bouyoucos cylinder (1 litre) and filled to the lower mark with distilled water while hydrometer was inserted and left on suspension. For the determination of the % sand, the hydrometer was removed from the cylinder and a stopper was used to block it. The cylinder was mixed thoroughly by inverting it severally times. The cylinder was later placed on lab bench and the time was recorded. It was left for 20seconds and the hydrometer was inserted carefully to read the gravity. This was repeated at 40seconds and the reading was recorded.

The hydrometer was removed from the cylinder and the temperature of the suspension was determined. 0.3 was added to the reading when temperature reading exceeded 20^0C, and 0.3 was subtracted from the thermometer reading when temperature was below 20^0C, (Udo and Ogunwale, 1986). Again, for the dispensing agent (sodium hexametaphosphate) added, 2 units should be deducted from every hydrometer reading. According to Ogunwale & Udo.

(1986) the hydrometer was calibrated to ensure the correct reading. The weight of the soil samples in suspension settled to the bottom of the cylinder after 40 seconds. The reading of the hydrometer after 40 seconds was determined, and this represented the amount of silt and clay in the suspension. The weight of sand in the sample was obtained by deducting the corrected hydrometer reading from the total weight of the sample (50g). The % sand was estimated by dividing the weight of sand by 50g (the weight of the sample) and multiplied by 100. After 20 seconds, the mass of sand obtained was used to determine the % of coarse sand while that obtained after 40 seconds was used to estimate the % of the fine sand. To determine the percentage of clay, the soil suspension was again re-shaken the hydrometer was inserted and the reading was taken after 2 hours. The temperature of the suspension was recorded and corrected by adding 0.3 to it. At the end of the 2 hours, the silt and sand settled out of the suspension. The corrected hydrometer reading at this time represented the grams (weight) of clay in the sample. The percentage clay was calculated by dividing this weight by 50g (the weight of the sample) and multiplied by 100. To determine the percentage silt, the sum of the percentages of both the sand and the clay was deducted from 100 to obtain the percentage silt.

4.5.3. Determination of pH

Soil pH is one of the most significant factors that affects stable element availability and transfer. Lower pH value results in higher mobility and transfer of cationic stable element and higher pH values reduce mobility and transfer of anionic metals (Li et al., 2009; Brokbartold et al., 2012; Kader et al., 2016; Antonaidis et al., 2017). This is because as pH increases, metal hydrolysis also increases thereby increasing metal sorption. pH increases the electromagnetic charge onto colloidal surfaces (including OM) thus increasing the soil retention capacity for cationic species (Shaheen et al., 2013; Wang et al., 2015). pH (potential of hydrogen) is defined as the negative logarithm of the hydrogen ion concentration in solution (Yuqing et al., 2005).

$pH = - \log10(H^+)$ where H^+ = Activity of Hydrogen ion in moles/litre

Procedure for pH determination: The soil to water ratio was made in ratio 1:1 (Udo & Ogunwale, 1986). Twenty grams of the fresh soil sample was weighed into 50 ml beaker and

20ml of distilled water was added and allowed to stand for 30minutes, and it was stirred with glass rod. The electrode of the pH meter was inserted into the partly settled suspension and the pH was measured. This was repeated for all the samples.

4.5.4. Exchangeable acidity by KCl extraction method

The 2mm sieved soil samples were weighed (2g each) into centrifuge tubes and 20ml of KCl solution was added to each centrifuge tube (1:10). The tubes were shaken on a mechanical shaker for 15min and the solution was filtered and drained into volumetric flask (perchlorate (KCl) extract). Three drops of phenolphthalein indicator were added to the potassium perchlorate extract and was titrated against 0.01M NaOH solution until a permanent pink endpoint. The endpoint readings(titre) was determined as the exchangeable acidity value. There is a need to always check the presence of Al^{2+} ion in the solution because the total exchangeable acidity is the summation of the total H^{+} and the Al^{2+} found in the medium (Udo & Ogunwale, 1986). Therefore, one drop of 0.01N HCl and 5ml of NaF were added to decolourise the solution while the solution was stirred continuously for 10min and observed for the solution to further turn pink. There was no further colour change during this process, which indicates Al was not detected in the solution. The exchangeable acidity was necessary to determine total soil acidity and Cation Exchange Capacity (CEC) (Coscione et al., 1998).

4.5.5. Cation Exchange Capacity (CEC) (summation method)

Cation Exchange Capacity (CEC) expressed in milli-equivalents per 100g of soil, is defined as the sum of exchangeable cations in the soil (summation of total exchangeable bases (TEB) and Exchangeable Acidity (EA). Total exchangeable bases were determined by using the extraction method. 1g of each of the soil sample was weighed and 20ml of 0.1M NH_4OAc was added. This was then shaken for 10minutes and allowed to settle. The filtrate was analysed with AAS for Mg and Ca while Flame photometer was used for Na and K. (IITA, 2016).

Estimation of CEC: CEC = Total exchangeable bases (TEB) + Exchangeable Acidity (EA)

4.5.6. Soil organic matter content determination (Walkley-black method)

Soil composition varies from place to place but a typical soil consists of about 45 percent minerals, 25 percent water, 25 percent air, and 5 percent organic matter (UNH, 2017). The

value for the percentage (%) organic matter content in the soil was calculated from the percentage organic carbon. The organic carbon content of the soil samples was determined as follows. The apparatus used were Burettes (50ml capacity), conical flask, 10ml Pipette and an automatic pipette. The soil samples were sieved through 2mm-sieve and 1g of the sample weighed out into 250ml conical flask.

Solution A: 49.04g of potassium dichromate ($K_2Cr_2O_7$) was dissolved in distilled water and the solution was diluted to 1litre. Ten millilitres were taken out of this solution and added to 0.5g of the soil sample each in conical flasks. These were arranged under fume chamber and 20ml of concentrated sulphuric acid (H_2SO_4) was added to each of the samples in the conical flasks and allowed to cool for 30min, distilled water was added to each solution in the flasks, and they were made up to 150ml. 3 drops of Ortho Phenanthroline-ferrous complex (0.025M) were added to the solution. Orthophenanthroline indicator (Ferroin indicator) was prepared by dissolving 14.85g of Orthophenanthroline monohydrate and 6.95g of $FeSO_4.7H_2O$ and diluted to 1litre (Udo and Ogunwale, 1986).

Solution B (Ammonium ferrous sulphate): 196.1g of ferrous ammonium sulphate Fe $(NH)_2(SO_4)_3.6H_2O$ was dissolved in 800ml of distilled water containing 20ml of concentrated (H_2SO_4) and this was diluted to 1litre. This was titrated against solution A with the Ortho phenanthroline indicator.

Solution C (Blank): Blank was prepared by adding 10ml of potassium dichromate ($K_2Cr_2O_7$) solution used in solution A and 20ml of concentrated sulphuric acid and made up to 150ml with distilled water then indicator was added. Solution C is categorised blank because there was no sample in it. B was first titrated against blank and the titre value was recorded. Thereafter, B was titrated against A and C, the titre value was recorded. Percentage (%) organic carbon = (Titre value of Blank – Titre value of Sample) × x

While $x = \frac{volume\ of\ K_2Cr_2O_7}{Titrevalueofblank} \times \frac{0.003 \times 1.33 \times 100}{Sampleweight}$

Volume of $K_2Cr_2O_7$ was 10ml, Titre value of blank was determined from the titration. NB (the soil sample weight used was 0.5g, 0.003 correction factor was used;1.33, Relative Atomic

Mass of carbon was used) and this was multiplied by100 to convert to percentage. After calculating the % Organic carbon, the value was used to calculate the organic matter content of the soil. Percentage organic matter content of the soil sample = %Organic carbon × 1.729 (IITA, 2016; Udo and Ogunwale, 1986).

4.5.7. Available phosphorus (Murphy and Riley method)

The 2g weight of soil was put into centrifuge tube and 20ml of extracting solution was added to each centrifuge tube (1:10). The tubes were shaken vigorously by mechanical shaker for 15min, it was filtered, 5ml was taken from the filtrate, and places in an extraction cup and 5ml of Murphy and Riley solution was added. Forty millilitres of distilled water were added, and it was allowed for 5min to attain the correct colour change. After about 5min, the colour turned blue and this was poured into sample cuvette (IITA, 2016; Murphy & Riley, 1962). Spectrophotometer (NV201 model), was used to read the phosphorus at wavelength of 882nm (IITA, 2016). Calculations:

Available phosphorus = (Extraction factor × Dilution factor) × x …….. equ 1

Where: Extraction factor = Extraction volume ÷ sample weight = 20 / 2 = 10, Dilution factor = 50ml / 5ml = 10

An equation was generated by the analytical equipment from the slope of the standard stock solution prepared (0.2mg/kg, 0.4mg/kg, 0.6mg/kg, 0.8mg/kg and 1mg/kg) which was used to calibrate the spectrophotometer. The graph of the concentration from the standard solution was a straight-line graph. The equation generated was:

Y= 0.784 x + 0.012……..- equ 2

Y = sample reading, x = constant and to derive$x$ from the equation 2;

x=Y − 0.0120.784 …….. equ 3

Y reading was obtained from the machine as the sample was placed and the value was substituted in the equation (3) and the value of x was calculated. The known values of X were

then substituted for in equation (1) to get the available phosphorus in each soil sample (IITA, 2016)

4.5.8. Nitrogen content by macro-Kjeldahl method

0.5g of the soil samples was weighed into digestion tube and 5ml of concentrated sulphuric acid (H_2SO_4) was added. One tablet of selenium (catalyst) was added to each sample and the digestion tubes were placed inside the digestion block (hot block). This was done for 3 hours at 360^0C until the brown fumes disappeared and clear light amber colour solution was obtained. The solution could cool for 1 hour and then transferred into 250ml standard volumetric flask. This was made up to mark by adding distilled water and further transferred into extraction cups as the digest (IITA, 2016).

Macro-kjeldahl Distillation: About 5ml of boric acid indicator was measured into 100ml conical flask and the flame was ignited under the distillation flask. The water allowed to boil to generate pressure and the conical flask containing the boric acid indicator was placed at the delivery end. Five millilitres of the digest were measured and poured into the distillation chamber and 5ml of 40% NaOH was added. It was covered and allowed to distil into the delivery chamber until 50ml pitch green distilled solution was achieved

4.6. Plant and animal tissue digestion

The sample extracts were prepared weighing 2g of the sample into the digestion vial and 10ml of aqua regia (1:3 of nitric acids and hydrochloric acid) was added. The mixture was then evaporated on the Q-block digester until the brown fumes disappeared leaving a white fume. The solution allowed to cool at room temperature and made up to 25ml using the volumetric flask. This was filtered with a Whatman filter paper and poured into white plastic bottles ready for analysis. Standard Reference Materials for vegetable and human hair (NIST NCS DC 73347/73348/73349/73350/73351) was digested the same way. At the minimum, n=5 samples of each RAPs were analysed, and for frogs higher n values were analysed. The whole body of the organism excluding gastrointestinal (GIT) system was analysed in all the samples and for earthworm, bees, composite samples of 15 and 30 individual organisms were sampled respectively.

4.7. The Microwave Plasma Atomic Emission Spectroscopy (MP-AES) analysis

The concentrations of stable elements as radionuclides analogues were determined by MP-AES.

4.7.1. MP-AES 4200 setup for stable element analysis

It is important to ensure that the exhaust line is secured, the gas lines, the spray chamber, nebulizer and peristaltic tubes are correctly connected before turning on the gas supplies. Turn on the power supply to power on the instrument (MP-AES 4200) and MP-AES software interface/open the valve of the nitrogen gas generator/compressed air supply and allow the instrument to warm up and initialise for 10 minutes. Turn on the auto-sampler power and rinse the instrument with rinse with (2 – 5% HNO_3) solution.

4.7.2. Analytical calibration procedure for MP-AES 4200

Appropriate concentrations range of working standards from the single or multi-elements stock standard was prepared through serial dilution method. Set appropriate conditions and parameters for fitting the calibration curve on the worksheet created from the MP-AES Expert software. Thereafter, the elements of interest and their wavelengths were selected. Input sample matrix, sample codes, blanks and standards in the appropriate rack position on the autosampler. Read blank first, then working standards. Check for the calibration coefficient and ensure regression equation of $R^2 \geq 0.995$. Recalibrate instrument with standard if lower than this value. When a suitable calibration fit is achieved, analyse an Independent Calibration Verification (ICV) to ensure precision of instrument and quality assurance/quality control (QA/QC) purpose. The percent recovery must be within ± 20%. Run samples and run continuous calibration standard (CCV) for QA/QC and instrument precision after reading about 20 samples. At the end of sample run, run blank and rinse solution for few minutes.

4.7.3. Calculations

Stable elements concentrations in liquid and digested solid sample were obtained directly from the instrument with the appropriate pre-set unit. For stable element concentration in solution, the value was expressed in ppm(mg/L) and for solid samples, all concentrations were calculated as mg/kg or ppm based on dry weight basis. Four replicates analytical results were generated by analytical equipment and standard deviations. Nine stable elements

concentration were determined using the MP-AES including Strontium (Sr), Caesium (Cs), Selenium (Se), Cobalt (Co), Uranium(U), Thorium (Th), Europium (Eu), Cerium (Ce) and Molybdenum (Mo). The different limits of detection for elements analysed were as follows (Se=0.184, Mo=0.0303, Th=0.0108, Co=0.0288, Ce=0.0097, Eu=.00085, Sr = 0.001145, U= 0.0836). The percentage recovery was calculated as follows:

% Recovery = Observed value / Reference value* 100

The instrument percentage retrieval was between 97.4% -100.33% which was a good measurement accuracy for the analytical equipment.

4.8. Results and discussions

4.8.1. Statistical method

Wildlife concentration ratios were extracted from IAEA database and other recently published papers (Beresford, Barnett et al. 2018, Guillen, Beresford et al. 2018). Two different comparisons were made

(a) Comparison of the data from the two research locations (Geregu and Itu).

(b) Comparison of all data including site specific data (GERITU), SSAD and IAEA.

(c) CRs data from Geregu and Itu were incorporated into the SSAD and compared with IAEA CRs.

ANOVA (parametric test) was chosen to test statistically significant difference between the data. The results of the statistical analysis are presented below. Further post hoc tests (Bonferroni and Duncan test) were conducted to determine significant differences between specific groups.

4.8.2. Results of the wildlife concentration ratios

The mean of the concentration ratios and standard deviation (SD) for n observations in RAPs are presented in table 4.8.1. Statistical comparison of the mean concentration ratios at the two case study sites (Geregu and Itu) for different RAPs organisms were also presented. The detailed descriptive statistics of the concentration ratios of wildlife is contained in appendix 6. The appendix 4 & 5 contained detailed biota and media (soil) concentrations used for deriving the concentration ratios. The comparison of the concentration ratio of small

mammal(rat) was not undertaken because only one rat sample was collected from Geregu and as such statistical comparison was not possible. Table 4.8.1 shows statistical comparison of caesium concentration ratios in different wildlife groups. In the table N represents number of observations, SD for standard deviation, DF= degree of freedom, F and P values.

Table 4.8.1. Caesium CRs in RAPs from case study locations

Wildlife	Element	Sites	N	Mean	SD	DF	F	P
Bee	Cs	Geregu	5	1.85E-02	5.30E-03	1	17.12	0.00
		Itu	5	7.43E-02	2.97E-02	8		
Earthworm	Cs	Geregu	5	1.73E-02	8.34E-03	1	20.70	0.00
		Itu	4	4.25E-02	8.19E-03	7		
Frog	Cs	Geregu	9	5.36E-02	1.75E-02	1	4.92	0.04
		Itu	9	1.06E-01	6.93E-02	16		
Grass	Cs	Geregu	5	1.67E-02	1.60E-03	1	13.21	0.01
		Itu	5	9.03E-02	4.52E-02	8		

The concentration ratios of caesium were significant (p=0.05) for all RAPs organisms analysed (bee, earthworm, frog and grass). Higher concentration ratios were observed with data from Itu compared to Geregu data. The highest and lowest transfer parameter for Cs was seen in frog from Itu and grass from Geregu respectively. Table 4.8.2 shows statistical comparison of strontium concentration ratios in different wildlife groups.

Table 4.8.2. Strontium CRs in RAPs from case study locations

Wildlife	Elements	Sites	N	Mean	SD	DF	F	P
Bee	Sr	Geregu	5	1.24E+00	5.00E-01	1	0.91	0.37
		Itu	5	2.08E+01	4.60E+01	8		
Frog	Sr	Geregu	9	4.47E+00	1.95E+00	1	2.54	0.13
		Itu	9	3.28E+00	1.10E+00	16		
Grass	Sr	Geregu	5	7.50E-01	1.03E+00	1	0.03	0.88
		Itu	5	6.29E-01	1.34E+00	8		

Sr= strontium, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values

The results presented in table 4.8.2 show no significant difference (p=0.05) was observed for bee, frog and grass for strontium. Sr concentration ratios in both locations were comparable

(within same order of magnitude) for both frog and grass. Table 4.8.3 statistical comparison of selenium concentration ratios in different wildlife groups.

Table 4.8.3. Selenium CRs in RAPs from case study locations

Wildlife	Elements	Sites	N	Mean	SD	DF	F	P
Bee	Se	Geregu	5	3.03E-02	1.93E-02	1	78.79	0.00
		Itu	5	1.44E+00	3.54E-01	8		
Frog	Se	Geregu	9	9.93E-02	2.09E-01	1	0.34	0.57
		Itu	9	1.45E-01	1.13E-01	16		
Grass	Se	Geregu	5	1.43E-02	1.55E-02	1	1.49	0.26
		Itu	5	3.06E-01	5.33E-01	8		

Se= selenium, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values

The mean selenium CRs was significant for bee samples at (p=0.05) but no significant difference was seen with frog and grass in both locations. Higher CRs values were observed for RAPs from Itu compared to Geregu. Variation of Se CRs were within 1-2 order of magnitude. Table 4.8.4 shows statistical comparison of uranium concentration ratios in different wildlife groups.

Table 4.8.4. Uranium CRs in RAPs from case study locations

Wildlife	Elements	Sites	N	Mean	SD	DF	F	P
Bee	U	Geregu	5	1.09E-02	7.26E-03	1	1.31	0.29
		Itu	5	8.89E-02	1.52E-01	8		
Frog	U	Geregu	9	2.92E-02	2.53E-02	1	1.90	0.19
		Itu	9	9.65E-02	1.44E-01	16		
Grass	U	Geregu	5	1.46E-02	1.24E-02	1	1.90	0.21
		Itu	5	5.60E-02	6.59E-02	8		

U= uranium, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values

Uranium concentration ratios were not significant in any of the wildlife sampled at (p=0.05). Higher CRs values were detected with Itu data except for earthworm where the mean of Geregu data was higher.

An overall comparison of CR values derived from the Geregu and Itu samples is presented in Figure 4.8. The mean CRs from Geregu were generally lower than those derived from Itu samples. However, there were some notable exceptions to this, such as the earthworm for which 5 out of the 9 mean CRs derived from Geregu samples were higher than at Itu.

	Geregu:Itu								
Element	**Fruit**	**Maize**	**Root**	**Vegetable**	**Bee**	**Earthworm**	**Frog**	**Grass**	**Rat**
Ce	3.26E-01	5.54E-01	5.48E-03	1.49E-01	9.15E-03	3.57E+01	2.16E+00	3.23E-01	1.44E-02
Co	1.80E-01	7.16E-02	2.85E-01	8.02E-02	5.89E-02	4.03E-02	1.12E-01	1.63E-01	4.68E-02
Cs	3.45E-01	1.80E-01	4.05E-01	4.97E-01	2.50E-01	4.06E-01	5.04E-01	1.85E-01	4.39E-01
Eu	6.86E-01	3.58E-01	7.94E-01	2.15E+00	1.13E-01	3.36E+00	8.20E-01	2.26E-01	2.91E-01
Mo	1.22E+00	1.21E-02	1.46E-01	2.42E-01	2.35E-02	1.08E-01	7.32E-01	1.93E-01	5.32E-02
Se	9.58E-01	1.75E+00	1.95E-01	5.35E-01	2.11E-02	7.56E-01	6.83E-01	4.66E-02	8.76E-02
Sr	3.09E-01	3.23E-01	2.42E-02	3.66E-02	5.96E-02	6.15E+01	1.36E+00	1.19E+00	1.80E+00
Th	4.65E-02	1.25E-01	7.81E-03	5.57E-02	1.26E-02	1.09E+00	3.77E-02	2.29E-02	5.71E-03
U	2.64E-01	1.85E-02	1.56E-02	7.27E-02	1.22E-01	2.99E+00	3.02E-01	2.61E-01	1.37E-02

Figure 4.8. Comparing the mean concentration ratios derived from Geregu and Itu samples. The marker colours indicate the extent of the difference between mean Geregu and mean Itu CR values: Orange > 10, yellow > 1, green > 0.1, grey > 0.01. Green and grey indicate that Itu CRs values were higher compared to CRs from Geregu.

4.9. Discussion on CRs of wildlife

Radionuclide transfer to wildlife has been assessed and concentration ratios (CRs) for different wildlife has been determined in two case study locations planned for the construction of nuclear power in Nigeria (Geregu and Itu). For stable caesium, the CRs between the two sites (Geregu and Itu) was compared and results suggest Itu CRs values to be higher in 1-2 order of magnitude compared to Geregu (Valesco et al., 2009). Different soil types exhibit different properties (soil mineralogy, pH, O.M and fertility) and these soil properties have different influence on caesium transfer. The higher transfer values obtained in data from Itu may likely be attributed to different factors including the influence of soil type and properties (Golmakani et al., 2008).

High strontium CRs (earthworm, frog and grass) were observed with data from Geregu while for bee and small mammal, Itu presented higher concentration ratios. No specific pattern was observed in Sr transfer between the two sampled location. For selenium, cobalt, uranium, all sites in Itu had high CRs (1-2) order of magnitude higher compared to Geregu in all wildlife analysed except in one site (earthworm- Itu for uranium element). Similarly, For Th, Ce, Eu and molybdenum, CRs value for Itu was higher except for the sites in Geregu where earthworm was obtained. In earthworm and for U, Th, Ce, Eu, and Mo higher values were obtained for Geregu CRs (up to two order of magnitude higher than values obtained from Itu). The highest CRs value was obtained for bee and CRs in RAPs decreases in the order Bee> frog>rat>earthworm and grass.

The results of the RAPs were compared with previous RAPs data from both Guillen et al. (2018) and Barnett et al. (2014) and there was good agreement between CRs of RAPs from this study and RAPs from the Guillen et al paper on Mediterranean ecosystem. For Cs, Se, Co and Mo values were in the same order of magnitude for earthworm, bee, frog, rat and grass with slight variation. In many of the RAPs mean CRs from this study was slightly higher than the mean of the Guillen et al paper except for selenium and molybdenum. Similarly, comparison with RAPs CRs from Barnett et al showed RAPs CRs from this study were higher for all elements except for selenium. Again, values of CRs for all stable elements were in same order of magnitude except for Co and U where CRs values were 1-2 order of magnitude higher than results presented in Barnett et al., 2014. Overall, there were good level of agreement

between RAPs CRs reported in this study and those of previous studies (Barnett et al., 2014; Guillen et al., 2018). The descriptive statistics results are contained in the appendix 6.

4.10. Assessment of dose rate using ERICA Tool

In recent years, there has been an increasing international interest in the assessment of doses and risks from ionising contaminants to biota resulting from exposure to radionuclides (Andersson et al., 2008; ICRP, 2007; Larsson, 2008). Several models are now available to enable the assessment of radiological risk to biota (Beresford et al., 2008a; Vives I Batlle et al., 2007). One of these models is the ERICA tool (Brown et al., 2008, Brown et al., 2016) which implements the ERICA integrated approach (Beresford et al., 2007, 2008; Larsson et al., 2008). This approach was developed within the EC 6^{TH} Framework programme. The dose rate to terrestrial biota(ICRP reference animals and plants) due to analysed stable elements of radionuclide analogues were estimated using ERICA Tool (version 1.2)(Brown et al., 2008; http://www.erica-tool.com/; Brown et al., 2008; Brown et al., 2016). The ERICA Tool enable estimation of dose rate to biota for terrestrial, fresh water and marine ecosystem for a set of default reference organisms (Brown et al., 2008; Brown et al., 2016). Aliyu et al. (2015) used the ERICA reference organisms and universal screening dose rate of $10\mu Gyh^{-1}$ to evaluate the potential risk of the planned nuclear power plant in Nigeria in 2015. However, the derivation of site specific CRs presents an opportunity to conduct a dose assessment of the planned nuclear power plant using the ERICA Tool. The main reason for the assessment was to test the ERICA Tool with data from a different geographical region, the SSA and to estimate dose rates resulting from the planned nuclear power plant in Nigeria. Site specific concentration ratios derived from stable elements for RAPs were used for the ERICA dose assessment. However, many international compilations and derivation of generic concentration ratio data like those from ERICA were heavily derived from stable elements as well as radioisotopes (Brown et al., 2008; Brown et al., 2016; www.wildlifetransferdatabase.org).

Already derived expected discharges from atmospheric dispersion modelling of the proposed nuclear power plant (Aliyu et al., 2015) and parameters associated with the running of the SRS-19 air transport model incorporated into the ERICA Tool were used for the dose assessment (Larsson et al., 2008; Brown et al., 2016). The ERICA Tool provides a tiered approach allowing the inputs of site-specific measured concentrations in biota and in media

to be used in tier 2 and 3 (Brown et al., 2008; Brown et al., 2016). The dose assessment was performed using the tier 2. The ERICA Tool contains parameters such as Occupancy factor which defines the fraction of time an organism spends at a given location in its habitat (Brown et al., 2016). Terrestrial organisms are assigned the occupancy factor of 1. The ERICA Tool performs dose estimation from input data by applying dose conversion coefficients and weighting factors of 10, 3 and 1 for various radiation components (alpha, beta, gamma) respectively (Brown et al., 2008). An uncertainty factor of 3 was applied at tier 2 assessment to account for model uncertainty of the method (Oughton et al., 2008). Total dose is the summation of internal and external weighted whole body absorbed dose rates (Brown et al., 2008; Brown et al., 2016). To enable assessment, the total dose rates are compared directly with selected screening dose rate and as suggested by Anderson et al. (2008), the default screening dose rate is $10\mu Gyh^{-1}$. Concentration ratios affect the internal activity concentration predictions for each organism. There is a likelihood that when site specific concentration is applied, the results might be different from using ERICA generic data. Already established in this chapter and previous, Sub-Saharan Africa concentration ratios are different compared to CR data from IAEA publication from which the ERICA generic data were derived. The advantage of dose assessment over comparing CRs as done in previous chapter will be to establish whether there is potential impact on doses from ionising radiation. It is a good approach to begin ERICA assessment with Tier 1, which is simple and a highly conservative screening assessment. It enables the use of screening dose to calculate the environmental media concentration limit (EMCL) for the most exposed organisms of each radionuclide (Brown et al., 2016). Tier 1 assessment aims to identify sites of negligible concern and remove them from further assessment. Risk Quotients (RQ) can then be obtained through comparing the input media concentration with the most restrictive EMCL for each radionuclide. RQ calculation is given as

$$RQ_n = MAC_n / EMCL_n$$

Where MAC is the measured media activity concentration for a specific radionuclide. RQ values can be less than one or greater than one. When RQ<1, then, the probability of exceeding the benchmarks is relatively low and the assessment can be terminated at the Tier 1 level. When RQ>1, it suggests a 5% probability that the benchmark has been exceeded and Tier 2 assessment is required.

The Tier 2 assessment is a less conservative screening, more interactive and enables the assessors to change screening dose rate and radionuclides referred to as default or generic parameters, while specific reference organisms can be selected (Brown et al., 2008) for a more realistic assessment. Evaluation can be undertaken directly against the screening dose rate with risk quotient generated for each reference organism selected for the assessment (Howard et al.,2008; Brown et al., 2008. Brown et al., 2016). At the end of the Tier 2 assessments, there are assumptions to be made if the predicted dose assessment is below screening dose rate of $10\mu Gyh^{-1}$.

(1) Exit the assessment, suggesting a high degree of confidence and that the impact is negligible.

(2) If the estimated dose is greater than $10\mu Gyh^{-1}$ then, there is a potential concern and the assessment can be refined and consideration for more expert judgement required. There is a likelihood that the assessment may progress to Tier 3. When concern is high, the assessment is reviewed and refined either at Tier 3. Table 4.10 shows annual discharged rates of the planned nuclear power plant (Aliyu et al., 2015).

Table 4.10. Annual discharged rates of the planned nuclear power plant at Geregu in Nigeria.

Radionuclide	**Half-life**	**Radionuclides Annual discharge (Bq/s)**
H-3	12.35 y	9.76E+05
C-14	5730 y	3.33E+05
I-131	8.04 d	1.08E+02
I-133	20.8 h	2.03E+02
Kr-85	10.756 y	2.13E+06
Co-60	5.271 y	3.23E+01
Cs-137	30 y	2.25E+01
Cs-134	2.062 y	2.54E+01
Sr-90	29.12 y	2.22E-01

Table 4.10 indicates the number of radionuclides assumed to be discharged to air annually by the planned nuclear power plant at Geregu in Nigeria (McMahon et al., 2013; Abubakar et al., 2015). Figure 4.10a and 4.10b ERICA predicted dose rates per organisms in 20km distance away from the planned nuclear power plant.

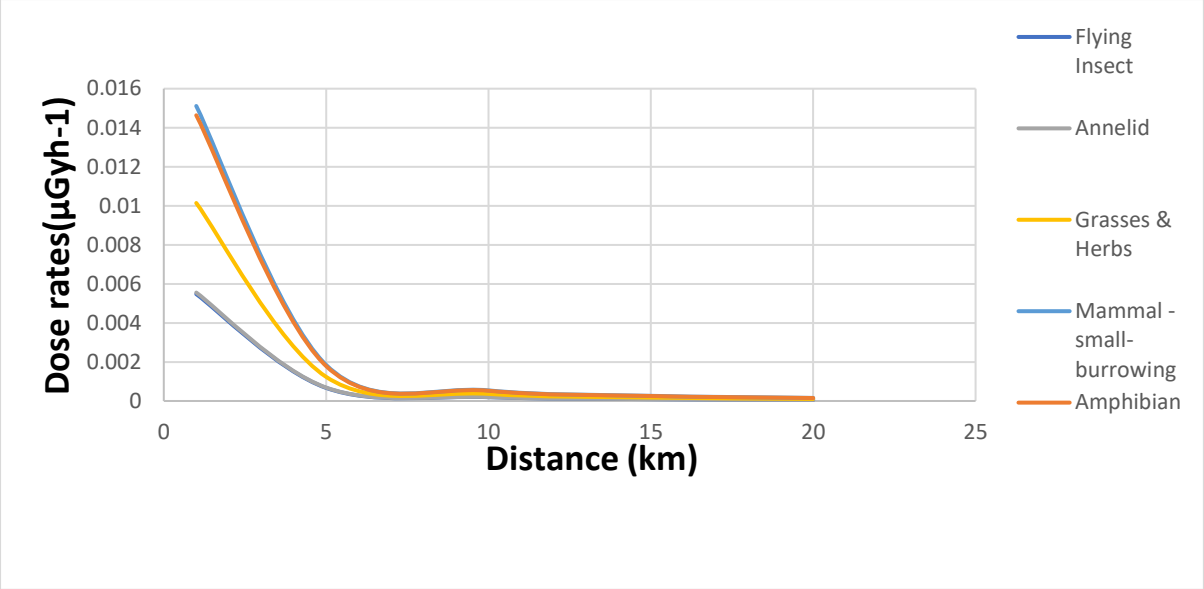

Figure 4.10a. Calculated doses relative to distance from the nuclear power plant (Brown et al., 2008, 2016

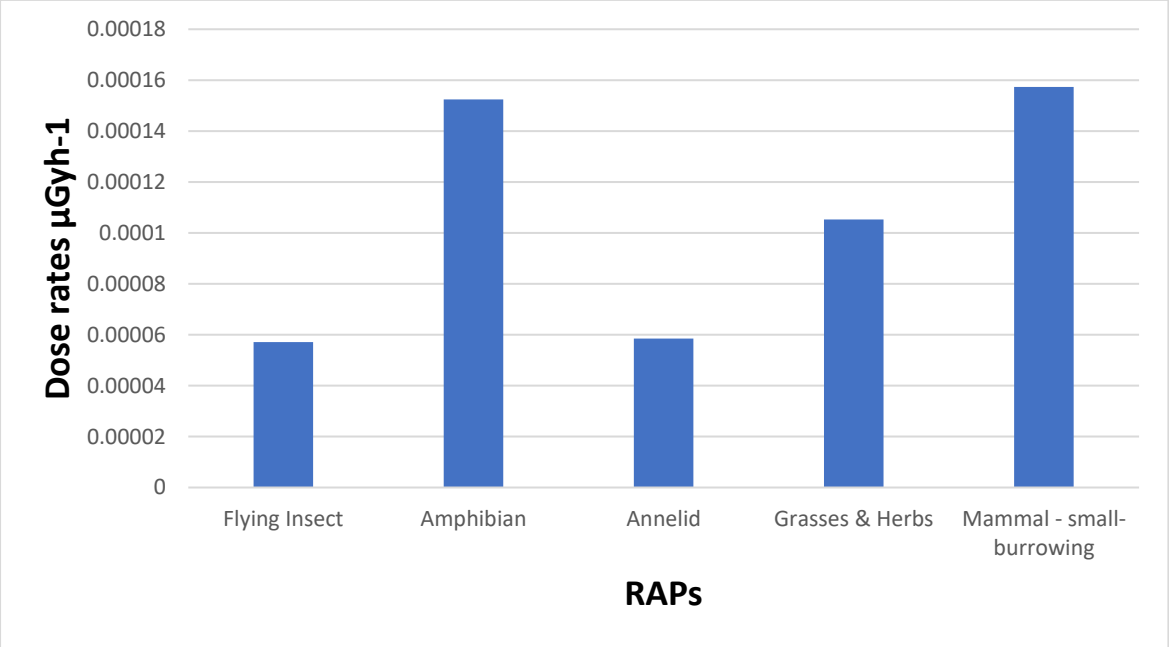

Figure 4.10b. Total dose rates per Reference Animals and Plants (RAPs) (Brown et al., 2016)

RAPs means Reference Animals and Plants

4.10.1. Discussion of dose assessment using ERICA Tool

The tier 2 assessment of the ERICA Tool has been performed and resultants dose rates per organisms are shown in figures 4.10a and 4.10b. The risk quotient (RQ) was <1 for all organism and therefore, the probability of exceeding the benchmarks is relatively low. The results of stable elements concentration ratios (mg/kg Fresh mass) of terrestrial ICRP RAPs from this study was used in the ERICA tier 2 assessment to estimate the potential dose rates per organisms and the results have been presented. Detailed dose rates at different distances from the nuclear plants are contained in the appendix 10. The expected discharged rates per for the reference organisms per year, obtained from Aliyu et al. (2015) and deposition height of 100m with soil bulk density of 1.48kgm^{-3} were used. The expected discharge duration was for 30years (Brown et al., 2008) and dose rates at different distance(1-20km) from the nuclear power plant was computed. 20 km by default is the distance the ERICA tool would predict based on SRS-19 and this prediction can be used to give a conservative assessment for other locations at greater distance. Except for Ajaokuta (7km away), other neighbouring towns to Geregu such as Lokoja (45km away), Okene (65km away), Idah (70km away) and Anyigba (71km away) would receive a conservative dose assessment. The dose rates calculated by Aliyu et al., 2015 using ERICA Tool were 5-6 order of magnitude lower than values from this study and the procedures Aliyu et al. (2015) adopted were not clear and as such dose rates would need to be reviewed. From the assessment at 20km distance away, small mammals and flying insects would receive the highest and lowest dose rates respectively as shown in figure 4.10b and the difference in dose rates in small mammals and flying insects were within an order of magnitude. From the graph in figure 4.10a, dose rates per organisms decreases with distance.

4.11. Food crops concentration ratios

The full descriptive statistics is available in the appendix 9. Appendix 7 and 8 contains food crops and soil concentrations used for deriving concentration ratios. Table 4.11.1, shows the results of caesium concentration ratios in food crops collected from Geregu and Itu

Table 4.11.1. Caesium concentration ratios for food crops from case study locations.

Food crops	Elements	Sites	N	Mean	SD	DF	F	P
Fruit	Cs	Geregu	5	1.19E-02	4.11E-03	1	74.07	0.00
		Itu	5	3.46E-02	4.21E-03	8		
Maize	Cs	Geregu	5	8.67E-02	3.70E-02	1	41.28	0.00
		Itu	4	4.81E-01	1.33E-01	7		
Root	Cs	Geregu	5	8.76E-02	4.57E-02	1	19.60	0.00
		Itu	4	2.16E-01	3.99E-02	7		
Vegetable	Cs	Geregu	5	0.113759	2.93E-02	1	62.94	0.00
		Itu	5	2.29E-01	1.38E-02	8		

Cs= caesium, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values. In all the food crops analysed, the concentration ratios of caesium are significantly different for the two case study sites. Higher CRs were observed with data from Itu (2-5 times higher) compared to Geregu data for caesium. Table 4.11.2 shows the results of strontium concentration ratios in food crops collected from Geregu and Itu.

Table 4.11.2. Strontium concentration ratios for food crops from case study locations.

Food crops	Elements	Sites	N	Mean	SD	DF	F	P
Fruit	Sr	Geregu	5	6.94E-02	4.88E-02	1	0.79	0.40
		Itu	5	2.25E-01	3.88E-01	8		
Maize	Sr	Geregu	5	6.14E-01	1.23E+00	1	0.03	0.87
		Itu	5	7.50E-01	1.32E+00	8		
Root	Sr	Geregu	5	7.73E-01	2.73E-01	1	6.81	0.03
		Itu	5	3.19E+01	2.67E+01	8		
Vegetable	Sr	Geregu	5	2.02E+00	1.39E+00	1	1.09	0.33
		Itu	5	5.51E+01	1.14E+02	8		

Sr= strontium, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values

Strontium mean concentration ratios was significant with root crops at (p=0.05) and for other food crops, there was no significant difference. Slightly higher CRs were observed with Itu data compared to Geregu data. Table 4.11.3, shows the results of thorium concentration ratios in food crops collected from Geregu and Itu

Table 4.11.3. Thorium (Th) concentration ratios for food crops from case study locations.

Food crops	**Elements**	**Sites**	**N**	**Mean**	**SD**	**DF**	**F**	**P**
Fruit	Th	Geregu	5	1.58E-03	0.01	1	1.25	0.30
		Itu	5	3.40E-02	0.65	8		
Root	Th	Geregu	5	6.29E-03	0.01	1	16.89	0.00
		Itu	5	8.06E-01	0.44	8		
Vegetable	Th	Geregu	5	1.20E-02	0.15	1	1.06	0.33
		Itu	5	2.14E-01	4.39	8		

Th= Thorium, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values

For the natural radionuclides (Thorium), the mean concentration ratios of fruit and vegetable, there was no significant difference detected. For the root crop(cassava), at (p=0.05) significant difference was observed and values for Itu were 2 order of magnitude higher compared to Geregu. Table 4.11.4 shows the results of cobalt concentration ratios in food crops collected from Geregu and Itu. In the fig 4.11.4, Co= cobalt, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values. For the stable elements (Cobalt) no significant difference was observed in all food crops.

Table 4.11.4. Cobalt concentration ratios for food crops from case study locations.

Food crops	Elements	Sites	N	Mean	SD	DF	F	P
Fruit	Co	Geregu	5	0.09	0.15	1	3.38	0.10
		Itu	5	0.49	0.46	8		
Maize	Co	Geregu	5	0.17	0.13	1	4.33	0.07
		Itu	5	2.30	2.27	8		
Root	Co	Geregu	5	0.17	0.12	1	2.21	0.18
		Itu	5	0.59	0.62	8		
Vegetable	Co	Geregu	5	0.31	0.07	1	3.97	0.08
		Itu	5	3.90	4.03	8		

4.12. Comparing the concentration ratios of wildlife in all locations (GERITU, SSAD& IAEA)

Tables 4.12.1, 4.13.1 and 4.13.2 compared CRs for GERITU, IAEA and SSAD for wildlife & food crops. GERITU is an acronym used to represents Geregu and Itu CRs combined.

Table 4.12.1. Stable elements concentration ratios of wildlife from GERITU, IAEA and SSAD.

Wildlife	Elements	Sites	N	Mean	SD	DF	F	P
Co	Annelid	GERITU	7	2.72E-01	5.85E-01	2	1.28	0.30
		IAEA	15	4.65E-01	3.67E-01	24		
		SSAD	5	1.59E-01	9.48E-02	26		
Co	Grasses	GERITU	10	6.78E-01	1.18E+00	2	13.32	0.00
		IAEA	57	4.53E-02	8.76E-02	94		
		SSAD	30	2.54E-02	2.49E-02	96		
Cs	Grasses	GERITU	10	5.35E-02	4.91E-02	2	0.41	0.66
		IAEA	52	3.49E-02	6.58E-02	66		
		SSAD	7	3.27E-02	1.99E-02	68		
Mo	Grasses	GERITU	10	1.99E-01	2.74E-01	2	3.94	0.03
		IAEA	19	1.07E+00	9.20E-01	54		
		SSAD	28	5.87E-01	8.91E-01	56		
Se	Mammal	GERITU	5	1.95E-01	1.35E-01	2	17.31	0.00
		IAEA	40	2.36E-01	2.54E-01	82		
		SSAD	40	4.75E-03	6.83E-03	84		
U	Grasses	GERITU	10	3.53E-02	4.98E-02	2	0.61	0.55
		IAEA	82	2.29E-02	3.22E-02	93		
		SSAD	4	2.75E-02	1.96E-02	95		

Table 4.12.1 shows the results of different stable elements concentration ratios in wildlife combination.

Co= cobalt, Cs= caesium, Mo= molybdenum, Se= selenium, U= uranium, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values.

Comparison of the three different datasets (GERITU, SSAD, IAEA) simultaneously in table 4.12.1, shows that significant differences have been detected in Grasses for U & Mo at (p=0.05) level of significance. In other stable elements (Cs, U) for grass, no significant difference has been detected. In some stable element wildlife combination such as Co (annelid), Cs (grass) and U (grass), CRs values have been observed to be comparable (within same order of magnitude) and no statistically significant difference have been observed. For where statistical difference exists (Co- grass, Mo- grass and Se-mammal) Duncan post hoc test have been performed to understand significance between groups. Tables of the Duncan test of significance are shown in appendix (11a-11c). For between Co- annelid, between SSAD and IAEA, there was no significant difference at level 1 (p=0.866) but at level 2 (p=1), GERITU was significantly different. However, for Mo to grass element combination, there was no significant difference between GERITU and SSAD at level 1 (p= 0.19) and between SSAD and IAEA there was no significant difference at level 2 (p=0.107). For Se to mammal stable element combination significant difference was detected. SSAD was significantly different from the other two groups IAEA and GERITU. However, between GERITU and IAEA there was no significant difference. The mean CRs for grass were in all three data for uranium in the same order of magnitude and comparable especially between IAEA and GERITU and no significant difference detected.

4.13. Comparing the concentration ratios of food crops in all locations (GERITU, SSAD& IAEA)

The table 4.13.1 Comparing food crops concentration ratios in all three data GERITU, IAEA and SSAD for cobalt

Table 4.13.1. Cobalt CRs for food crops in all three locations (GERITU, IAEA and SSAD).

Elements	FCs	Sites	N	Mean	SD	DF	F	p
Co	Cereal	GERITU	5	2.93E-01	1.73E-01	2	58.55	0.00
		IAEA	65	3.65E-02	4.12E-02	83		
		SSAD	16	6.98E-02	7.40E-02	85		
Co	Legume	GERITU	5	1.46E-01	7.50E-02	2	2.14	0.12
		IAEA	105	6.26E-02	8.86E-02	134		
		SSAD	27	6.67E-02	8.78E-02	136		
Co	Maize	GERITU	10	1.23E+00	1.89E+00	2	21.94	0.00
		IAEA	77	4.06E-02	4.06E-02	131		
		SSAD	47	7.71E-01	3.09E+00	133		
Co	Root	GERITU	10	3.79E-01	4.78E-01	2	0.79	0.45
		IAEA	16	1.54E-01	1.34E-01	161		
		SSAD	138	3.30E-01	5.86E-01	163		
Co	Vegetable	GERITU	10	2.11E+00	3.28E+00	2	0.20	0.82
		IAEA	7	1.56E-01	5.60E-02	587		
		SSAD	573	2.88E+00	1.20E+01	589		

Co= cobalt, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values

The result of Cobalt in different food crops in table 4.13.1 showed that there was significant difference in concentration of Co in cereal and maize. Higher concentrations were recorded in the research site specific data (GERITU). The lowest concentrations were observed in IAEA data. The results of the post hoc test is shown in appendix 11 and the Duncan test showed that between SSAD and IAEA, the difference in concentration ratio was not significant at level 1 (p=0.99), however, GERITU was more significant at level 2(p=1). Similar results were obtained for maize at level 1(p=0.89) no significant difference between IAEA and SSAD. Same with legume, no significant difference between IAEA and SSAD but GERITU is more significantly different. Site specific data were 2-3 order of magnitude higher than IAEA and SSAD. For the concentration ratios of root crops and vegetables there was no significant difference in cobalt in all (GERITU, IAEA and SSAD). The table 4.13.2 compared different stable elements for the 3 data sets

Table 4.13.2. Concentration ratios of different elements and food crops from GERITU, IAEA and SSAD.

Elements	FCs	Sites	N	Mean	SD	DF	F	p
Cs	Root	GERITU	9	1.45E-01	7.90E-02	2	9.24	0.00
		IAEA	93	7.41E-02	1.43E-01	106		
		SSAD	7	3.07E-01	1.96E-01	108		
Sr	Legume	GERITU	5	6.37E-01	5.88E-01	2	4.96	0.01
		IAEA	148	2.00E+00	1.32E+00	153		
		SSAD	3	3.59E+00	5.37E-01	155		
Sr	Vegetable	GERITU	10	2.85E+01	8.07E+01	2	1.50	0.24
		IAEA	19	1.03E+00	1.90E+00	33		
		SSAD	7	2.35E+00	1.96E+00	35		
U	Root	GERITU	10	2.40E-01	5.87E-01	2	3.92	0.02
		IAEA	83	5.86E-02	9.37E-02	96		
		SSAD	6	2.01E-02	2.15E-02	98		

Cs= caesium, U= uranium, Sr= strontium, n= number of observations, SD= standard deviation, DF= degree of freedom, F and P values. Figure 4.13 summarised graphically the concentration ratios for three different environment, case study locations, IAEA and SSAD. The acronym GERITU- was used to describe the concentration ratios of the two case study locations combined.

U and Cs concentration ratios in root crops in table 4.13.2 showed significant difference and Sr was significantly different for legumes in the three datasets. Sr concentration ratios in vegetables were not significant. The natural radionuclides (uranium) at (p=0.05), there was a significant difference in concentration ratios of uranium (root) in all three datasets. The post hoc Duncan test. Cs, root and Sr (legume) crops (no significant difference between IAEA and GERITU respectively) but SSAD is more significantly different. For uranium root (no significant difference between SSAD and IAEA). However, GERITU is more significantly than SSAD and IAEA.

Figure 4.13 summarises the comparison of mean IAEA: SSAD CRs. This figure has incorporated the CRs results from Geregu and Itu into the SSAD. The result suggests that majority of wildlife and crop mean CRs in SSAD were greater than those in the IAEA data compilation, although there were a few instances where IAEA CRs were greater than SSAD. Apart from figure 4.13, helping to fill data gaps missing from the systematic review in the previous chapter (figure

3.4), the figure also suggested that CRs for both wildlife and food crops were different from IAEA CRs data.

		IAEA:SSAD																			
		Cs-137	Cs	Rb	Ra-226	Sr	Co	Cr	Mn	Mo	Ni	Pb	Cu	Zn	Sb	Se	Ce	Eu	U	U-238	Th	Th-232
Wildlife	Grasses	5.32E+00	8.10E-01	2.55E-01	2.58E-01	7.65E-02	1.29E-01	1.33E+00	2.02E+00	2.73E+00	1.27E+00	1.48E+00	2.75E+00	2.03E+00		1.09E+01	7.02E-02	3.04E-01	7.30E-01	5.69E-01	2.70E-01	1.63E-01
	Herbs		1.62E+00	1.07E-01	3.57E-01	1.07E+00	1.86E-01			8.51E-02							2.66E+00	2.04E+00	1.04E+01	2.28E+00		9.40E-02
	Grasses & Herbs		2.34E+00		6.58E-02																	2.36E-01
	Tree		2.62E-01	1.47E-02		5.02E-03		1.04E-02	4.01E-01		3.80E-02	1.01E-01	1.11E+00	1.32E+00								
	Macroalgae																					
	Amphibian		4.22E-01			2.11E-02	5.77E-02	2.09E-02	1.97E-02	4.19E-01	6.60E+00	5.22E-02		1.36E-01		3.02E+00			1.15E-02			
	Annelid		4.14E-01			2.89E-01	2.16E+00	1.61E-01	1.65E+00	6.10E+00	5.82E-02	5.69E-01		5.24E+01		4.96E+01	2.53E-03	3.11E-02	2.10E-01		2.37E-03	
	Arthropod		3.17E-01			5.21E-02	1.69E-01	5.93E+00	1.15E+02	4.34E-01	1.28E+01	1.14E+01		8.58E+02		2.13E-01	7.82E-04	3.31E-02	2.96E-02		2.54E-02	
	Crustacean																					
	Fish																					
	Mammal		5.69E-01			3.82E-01	1.11E-02			6.18E-01		4.10E+00				2.36E+00	3.38E-04	5.72E-01	4.36E-03		9.66E-04	
Crop	Root		3.28E-01			1.15E-01	4.35E-01		6.86E+00			4.20E-01		9.24E-01	1.44E-03				4.51E-01		1.28E+00	
	Tuber		4.06E+00			1.57E-01	5.98E-01		3.68E-01			1.04E+00		3.91E-01					1.71E+00			
	Vegetable		2.99E-01			6.66E-02	6.27E-02		1.64E+00			5.00E-02		1.06E+00					2.19E-01		2.15E-01	
	Leafy Vegetable					1.10E+00	1.44E-01		9.55E-01			9.68E-01		1.68E+00								
	Maize		3.82E-01			1.00E+00	2.01E-03		2.27E-01	1.99E-01		2.37E-03		9.81E-01					2.55E-02		2.05E-04	
	Legume		7.05E-01			9.49E-01	5.89E-01		1.55E+00			3.37E+00							7.44E+00			
	Cereal		2.04E+00			5.26E-01	2.01E-01		4.65E+00		5.75E-02	7.58E-02		3.96E+00			1.45E+00		1.36E+00		4.78E-02	
	Fruit											4.71E-03							2.18E+02			

Figure 4.13. Comparing concentration ratios of IAEA and SSAD (with Geregu and Itu CRs incorporated). The orange markers indicate IAEA:SSAD ratios greater 10, yellow markers indicate ratios >1 (i.e. 1-10), green markers indicate ratios <1 and grey <0.01. Elements are grouped according to the periodic table groupings.

4.14. Discussion of CRs of food crops (Geregu and Itu)

Many of the results from the analysis of food crops showed high transfer in stable elements-food crops combinations from Itu compared with Geregu. CRs value order of magnitude ranges from 1-2 and the highest CRs values were obtained from Itu. From previous studies, nitisols under high acidity and low exchangeable K condition results in high transfer of Cs (Barescut et al., 2005). Results from this study established that there was a variation in the transfer of Cs for food crops (vegetable, maize, roots and fruits). Vegetable and maize showed higher CR in Itu compared to Geregu for stable caesium. However, for root crops and vegetables Cs CRs were twice higher for Itu compared to Geregu. Similar trend was observed with strontium, selenium and uranium and for other stable elements such as Mo, Eu, Ce, Co, Th, a few high CRs from Geregu data were observed. All strontium CRs were higher for Itu compared to Geregu for all four crops (maize, root, fruit and vegetables). Root crops, vegetables and fruits in Itu, showed comparatively high CRs in all stable elements except for Mo and Eu. Overall, the average CRs in the food crops decreases in the order Maize>Vegetable>Root> fruit. Results of this study agrees with past literature that stated vegetables have higher transfer than fruits (Twining et al., 2004).

The estimated CRs values showed an interesting result particularly when comparison was made with other CRs values from the tropics and comparison with IAEA values which indicates the best estimates of CRs values (IAEA, 2010). Considering uncertainties in CRs values reported, transfer values differences of 1-2 order of magnitude may be considered not substantial, given that CRs values may show variation of up to 5 order of magnitude (IAEA, 2010). We compare transfer from case study location with other previously reported food crops transfer factors in both tropic and temperate environment. Previous literatures suggested higher accumulation is expected in crops growing sandy soils for Cs and Sr (IAEA, 2010). However, transfer values for Sr were higher compared to those of Cs in all stable element's food crop combinations. Analysing elemental analogous effect, it was observed that Ca(17.4cMol/kg) level in Itu was lower compared to Geregu (Ca=55.4cMol/kg). At lower

concentration of Ca, transfer of Sr is higher, and this may likely be responsible for higher Sr transfer in Itu compared to Geregu. Similarly, it was observed that potassium (K) concentration (0.2cMol/kg) is lower for Itu compared to K (0.6cMol/kg) concentration in Geregu soil. Again, higher transfer values for Cs were recorded in Itu for all food crops compared to Geregu and this may be attributed to analogous elements competitive effects. Chemical similarity between Cs and K, makes plants sometimes find it difficult to distinguish between them at such soils with trace amount of vermiculites, high concentration of exchangeable potassium would lower Cs root uptake due to Cs fixation to soil (Twining et al., 2004). When exchangeable K is low then high Cs transfer is likely (Wasserman et al., 2005). For soils from Itu, the pH (4.7) is lower than soils from Geregu with higher pH values (5.5). Also, OM is higher for Itu (3.0) and lower value obtained from Geregu (2.1). According to Twining et al (2004), Cs transfer is enhanced at a pH value approximately 4.5 and at increased soil organic matter content. The higher Cs transfer in Itu may likely be due to low soil pH and higher OM content in Itu compared to Geregu.

4.15. Conclusion

In this chapter, the results of transfer values for a range of food crops wildlife and associated stable elements were presented. The wildlife results presented here included those required for ICRP environmental protection framework (ICRP reference animals and plants- RAPs). This is an important part of this study as there were no previous data for most of the RAP presented in this study, at such the results will contribute to the development of a transfer database for SSA as well as to the development of an international radiological environmental protection framework with the hope for further integration of results to the IAEA working group on semi-arid environment. For the food chain, CRs values would be included in the food chain transfer database and parameter values useful for assessment of human food chain contaminations.

Strong contrasts of transfer parameters between case study sites, SSAD and international Atomic Energy Agency have been established for both human food chain and non-human biota. Variability between stable element concentrations may be attributed to soil factors, chemical behaviour of stable elements such as chemical analogues, plants and other environmental factors. The concentration of stable elements was generally higher for Itu compared with Geregu in all food crops. Similarly, wildlife obtained from Itu showed higher

concentrations compared to Geregu except for earthworms and amphibian. Comparing the site specific CRs (GERITU) with international IAEA data, the results confirm that most stable element concentrations in food crops and wildlife, showed higher concentrations for GERITU site specific data compared to data from IAEA. CRs values were 0-1 and 1-3 order of magnitudes higher for wildlife and food crops respectively. Site specific CRs data (i.e. Geregu and Itu) incorporated into the SSAD and compared with IAEA CRs revealed that majority of the SSAD CRs were greater compared to IAEA CRs.

Finally, in this chapter, Tier 2 ERICA assessment has been undertaken to assess the potential risk and environmental impact of the planned Nigeria nuclear power plant. Based on the ERICA Tool assessment, the risk for terrestrial biota that may be arising from ionising radiation from the nuclear facility when constructed is negligible. Tier one assessment showed that the risk quotient was below the benchmark values (RQ<1), therefore the probability of exceeding the benchmark is negligible. The results of the dose assessment obtained here is theoretical and once the nuclear plant becomes operational, then direct measurement can be performed, and new measurements based on real measured values conducted.

5. ASSESSING THE RADIOCAESIUM INTERCEPTION POTENTIAL (RIP) IN A SEMI-ARID ENVIRONMENT, A CASE OF THE NIGERIAN SOIL

5.1. Abstract

Many radiological models have been developed to enable prediction of radionuclide transfer from contaminated soils to the food chain which is an important step towards preparing for and responding to nuclear emergencies. To accurately predict the transfer of radiocaesium (^{137}Cs) from soil to food chain, it is essential to understand the interaction between caesium and the soil components (Ogasawara et al., 2013). Radiocaesium may be released during nuclear weapon detonation or nuclear accidents and when it is deposited in soils it remains available for many years (Tarsitano et al., 2011). Radiocaesium in soil is readily available and may become absorbed by crops through their root and eventually may find its way to the edible parts of human foods (Absalom et al., 2001). When absorbed by plant it can contaminate agricultural and human food chain. Health risks have been associated with long term intake of radiocaesium from human food and the consumption of these foods would lead to an increase in internal dose of the radionuclides. The extent of radiocaesium retention in soil plays an important role in understanding caesium contamination of food chains. Several studies have been conducted to determine Radiocaesium Interception Potential (RIP) in European soils for which it has been used to characterise soils/soil minerals' ability to selectively adsorb radiocaesium (Cremers et al., 1988). However, according to Vandebroek et al. (2012), tropical or subtropical soils have received little consideration for RIP measurement and for Sub-Saharan Africa, this study is the first of its kind to undertake RIP measurement in Nigerian soils. Sixteen principal soils from Nigeria in three replicates each were collected and analysed. The major soil types were identified using the FAO Nigerian soil map. RIP measurement was determined in the soil samples and the ranges were between 14.4-2470 mmol/kg. Other soil parameters and chemical properties (including exchangeable potassium (K^+), Cation Exchange Capacity (CEC) and clay content) were determined.

A semi-mechanistic model to predict uptake of radiocaesium by plant based on soil characteristics has been described by Absalom et al (Absalom et al.,1999, 2001). Three soil parameters are required by the model to estimate radiocaesium bioavailability and uptake by plants and these include labile caesium distribution coefficient (K_{Dl}), K^+ concentration in the soil

solution (M_k) and the soil solution to plant concentration factor (CF, $Bqkg^{-1}$ plant/ $Bqdm^{-3}$). These three parameters were derived as a function of five soil characteristics (soil clay content, organic matter (OM) content, pH, exchangeable potassium(K^+), ammonium concentration (Absalom et al., 2001) and the time since radiocaesium entered the soil. The determination of these parameters in the Nigerian soil presented the opportunity to establish a spatially implementable model for radiocaesium using the Absalom (or SAVE) approach (Absalom et al., 2001; Crout et al., 2009). RIP data obtained from the Nigerian soil were then applied to the "Absalom approach". This approach did not predict well for Japanese soils after the Fukushima accident, raising questions to its applicability in other regions of the world.

5.2. Introduction

Caesium can be a major component of all accidental releases as demonstrated by Chernobyl and Fukushima Nuclear power plant in May 1986 and March 2011, respectively and to a lesser degree Windscale in 1957 (Absalom et al, 2001, Chino et al, 2011). Major accidents (Windscale, Chernobyl and Fukushima) resulted in comparatively large-scale contamination. In the case of Chernobyl, this impacted on many countries, leading to the need for implementation of countermeasures, in some cases for decades and until the present-day (Absalom et al, 2001). Radiocaesium is of environmental and public health concern due to its relatively long half-life (about 30 years), comparatively high mobility, biochemical similarity to potassium (K) (Vandebroek et al, 2011) and hence potential for uptake and contamination of the human food chain (Merz et al., 2013; Beresford et al., 2016). The contamination routes can be through the foliage or root or both and interception and absorption by foliage can contaminate food crops and pastures for months (Almahayni et al., 2019). Deposition in soils and uptake via plants route could last for decades and therefore requires planned and implementable long-term countermeasures (Wright et al., 2003). Radiocaesium can be retained in the topsoil and selectively bind to soil particles especially clay minerals (micaceous) for a very long time (Vandebroek et al, 2012). Vertical migration rates or mobility of ^{137}Cs in agricultural soils is usually very low (Almgren and Isaksson, 2006) and transfer to edible parts of food crops is via root uptake and can thus pose long term risks of human exposure via ingestion. Radiocaesium availability may vary between soil types (Absalom et al, 2001). However, high amounts of organic matter may facilitate radiocaesium (RCs) contamination of food chain as can be observed in areas with a high level of organic soils. The fate of RCs is governed by selective sorption usually between

weathered clay layer (called frayed edge sites (FES) (Brouwer et al., 1983, Cremers et al., 1988). These specific sites in clays (especially 2:1 clay- vermiculites, illites, smectites), control radiocaesium (RCs) adsorption in soil (Cremers, 1983, Rigol et al., 2002). The interaction of RCs occurs on the cation exchange sites (mainly OM and clay). Since radiocaesium bio-availability is strongly affected by soil properties, some useful models have been developed to predict the activity concentration of radiocaesium in plants, using readily available soil characteristics (exchangeable K, % clay, organic matter, CEC and solid-liquid distribution coefficient (K_{Dl}) (Absalom et al, 2001). Many experimental approaches have been used to quantify radiocaesium retention, among these is the Radiocaesium Interception Potential (RIP) (Cremers, Elsen et al. 1988). RIP is defined as the ability of clay minerals (illites, mica) through the FES to selectively retain radiocaesium (RCs) therefore reduces its mobility and availability to plant (Sweeck et al., 1990). More specific definition regard RIP as the product of the $Cs^{++} \leftrightharpoons (K^{+} + NH4^{+})$ exchange constant and the content of Cs^{+}/K^{+} /$NH4^{+}$ specific sites (Absalom et al.,2001) and according to Uematsu et al. (2015), it is the parameter used to quantify sorption characteristics of radiocaesium on frayed edge sites. However, RCs adsorption can occur in non-specific sites only in organic soils with more than 95% of OM content and negligible clay.

5.3. Rationale for the study

Radiocaesium is major component of discharges from a nuclear reactor and long-term implementable remedial actions needs to be planned (Raskob et al., 2018). Therefore, in the event of emergency preparedness and responses, the study of radiocaesium interception potential and modelling RCs soil- plant transfer semi- mechanistically, using soil characteristics is important (Almahayni et al., 2019). In addition, soil in the tropical and subtropical environment which are dominated by 1:1 clay mineral and are different from soil in the temperate in terms of percentage composition and mineralogy (Six et al., 2002). Available evidence from the literature, suggested that Nigerian soils, are predominantly kaolinitic soil (Ojanuga, 1979; Akpanikan et al.,1987; Igwe, Akamigbo et al., 1999; Eshett et al., 1989; Abe et al., 2009). However, in European soil, the dominant clay minerals are the 2:1 clay soil, which are mainly illite, vermiculite and mica. (Wilson et al., 1984; Loveland et al., 1984). European soil differs from soils from Nigeria; therefore, it is important to establish that the semi mechanistic model would apply to the Nigerian soils for the purpose of future planning and management. Absalom model was configured using European soils which are different from SSA soils, there may be a question of

whether this model is applicable to the Sub-Saharan Africa. On the contrary, the lesson learnt from the application of existing European model to RCs transfer in Fukushima renewed interest especially in RCs transfer modelling to a wide range of environmental conditions (Hinton et al., 2013; Almahayni et al., 2019).

5.4. Bioavailability of radiocaesium in soil-plant systems

Soil physical and chemical characteristics affect radiocaesium availability to plant (Sanchez et al., 1999, Bunzl et al., 2000; White and Broadley, 2000; Ehlken and Kirchner, 2002; Fesenko et al.,2002; Staunton et al., 2003; Beresford et al., 2007; Mihsra et al., 2016; Burger and Lichtscheidl, 2018). Low soil exchangeable potassium (K^+), low solid-liquid distribution coefficient, low clay content and high $NH4^+$ concentration in the soil solution can influence high RCs transfer (Rigol et al., 2002). The mobility of RCs is more enhanced in organic soils as compared to mineral soils and much higher mobility was reported in organic-clay soils compared to organic soil (Cremers et al., 1988; Rigol et al, 2002; Staunton et al., 2002). Similarly, soil clay mineral types influence RCs retention or transfer (Waegeneers et al., 1999;). Sorption on soil constituents' controls RCs mobility and transfer to plants and at such the selectivity coefficient of radiocaesium against other species depends on species and the sites of the solid phase involved in RCs interaction. For example, in mineral soils such as illites and micas, the frayed edge sites (FES) selectively retain radiocaesium reducing its mobility and availability to plant. The abundance and selectivity of FES in soil is commonly described with the term radiocaesium interception potential (RIP) (Cremers et al., 1990, Sweeck et al., 1990). The 2:1 clay such as illites and micas also present high RIP values due to abundance of RCs adsorption sites (FES) (Waegeneers et al., 1999). $NH4^+$and K^+ are the major competitive species for RCs adsorption at the specific sites (Rigol et al., 2002), while Ca^{2+} compete with RCs on a non-specific site. Soluble K^+ in soil solution affects RCs transfer to plants while in soil it enhances RCs mobility in soil through competition for sorption sites (Absalom et al., 1999). White and Broadley, (2000) stated that K plays a major role in Cs uptake from soil. Soil micro-organisms such as Mycorrhizal are involved in symbiotic relationship with plant roots and have played a role in plant nutrient uptake especially in organic soils (Parekh et al., 2008), however, recent evidence suggested little contribution of mycorrhizal to RCs uptake by plants (Boulois et al., 2008)

According to Nakao et al. (2014), RIP has been positively correlated with some soil properties such as the K content for smectite and micaceous soils. Micaceous clay mineral absorbs ^{137}Cs

more than smectite (expansible 2:1 clay) (Zachara et al., 2002). According to Nakao et al. (2014), relatively small RIP values were found for both amorphous and kaolinitic clay minerals. Similar low RIP values were also observed for kaolinitic soil (Nakao et al.,2009). In contrast, all soil groups belonging to the micaceous, vermiculite and chloritic groups have high RIP values (Nakoa et al., 2014) this in part is because of the presence of FES at the intermediate site between the clay minerals which demonstrated significant correlation exists between total clay and exchangeable calcium and suggested that this was due to exchangeable calcium residing in the clay fraction which also stabilises the clay mineral. RIP clay has been observed to decrease slightly with increasing organic matter (Sanchez et al., 1999).

5.5. Modelling radiocaesium (RCs) transfer to food chain

Soil properties such soil texture and potassium status have major effects on soil to plant transfer of radiocaesium (Guivarch et al., 1999; Zhu et al., 2000). Several food chains models have been developed to predict RCs transfer to plant. The empirical model relies on soil to plant transfer factor to estimate radiocaesium activity concentration (conventional CRs approach) (Nisbet and Woodman, 2000; Frissel et al., 2002; IAEA, 2010) and the mechanistic models are largely based on plant nutrient transport and uptake mechanism to simulate transfer of RCs (Oates and Barber, 1987; Kirk and Staunton, 1999). BioRUR model predicts RCs based on the ratio of potassium uptake to RCs concentration in soil solution using the selectivity coefficient and discrimination transport mechanism between K and RCs (Casadesus et al., 2008). None of these models are suitable for emergency and response conditions due to large variability, and disregard soil and plant parameters or simply too complex for emergency purposes except for the semi-mechanistic model which requires few inputs and regards to soil parameters (Almahayni et al., 2019).

5.5.1. Absalom model

Nisbet and Woodman (2000) by analysing a large database of radiocaesium transfer factors found that transfer factor of radiocaesium appeared to be independent of RCs concentration in the soil. Further analysis of trends showed that the uptake of RCs can be predicted from soil solution concentration of both Cs and K (Smolder et al., 2000). This argument led to the use of transfer factor approach and the development of the (Absalom et al., 1999) model to predict plant uptake of radiocaesium from readily available soil parameters (Absalom et al., 1999). The Absalom

approach is a semi mechanistic approach which factorises the effects of soil characteristics on radiocaesium transfer (RCs) (Almahayni et al., 2019). This model defined the distribution of solution ^{137}Cs and sorbed ^{137}Cs as the labile distribution coefficient (K_{Dl}), dm^3kg^{-1}, estimated as a function of soil clay and exchangeable K^+ (Absalom et al., 1999). Plant uptake of radiocaesium, described by a concentration factor (CF, $Bqkg^{-1}$ plant/ $Bqdm^{-3}$), was defined as the ratio of radiocaesium activity concentration in plant (Cs-plant) to that in the soil solution which was related to K^+ concentration (M_k), moles dm^{-3}. Arguably, the Absalom 1999 model, was limited to grasses, mineral soils, no consideration for organic soils and short period of contamination (<100 days). Absalom et al. (2001) model was applied to measurements made in 53 well characterised soils from two pot trials involving two crops; ryegrass (*Lolium perenne* grown on mineral soil) and bent grass (*Agrostis capillaris* grown on organic soils) (Sanchez et al., 1999). Absalom et al. (2001) model has been applied for the modelling of long-term transfer of radiocaesium in Ukraine by workers. Gillett et al. (2001) and Cos et al. (2005) applied it for spatial prediction in England and Wales respectively. Cox et al. (2001) used it for the optimisation of long-term countermeasure management respectively. The model initial applications on a range of soil and crops combinations revealed good agreement with observed values (Smolder et al., 2000). Simon et al. (2002), could not apply the model to carbonate soils of the Marshall Island atolls and its vegetation, indicating that model only work best when applied within the range of conditions for which it was developed. In 2005, the Absalom model evaluation was undertaken, and the model was able to make a prediction for grass vegetation but performed poorly with rice. At such, the model was extended to include tropical plants and soils (Rahman and Voigt, 2004; Rahman et al., 2005). This semi mechanistic model, Absalom 2001 model, has been incorporated in the ARGOS nuclear emergency decision support system, a system maintained by an international consortium of ten countries which further reemphasised the importance of the model (Tarsitano et al ., 2011; www.pdc.dk/argos). However, Absalom et al. (2001) model has been re-parameterized, and the re-parameterised model was applied to the Nigerian soil to predict RCs transfer factor.

5.6. Materials and methods

5.6.1. Sampling location

Nigeria was chosen for the study campaign to represents the semi-arid region for which the sub-Saharan Africa belongs. Sub-Saharan Africa showed variable climatic conditions and soil types (Waha et al., 2013). The vegetational zones across Nigeria are broadly divided into the savannah

(North) and forest (South) vegetation with further sub- vegetational zones within the majors vegetational types. There are abundant uncultivated grassland and natural environments, dominated by grasses, shrubs and woody vegetation (Bandyopadhyay et al., 2012). The derived savannah' is a transition between the two vegetational zones and within each zone, important seasonal differences exist (Oguntoyinbo, 1970). The region's terrestrial ecosystem is typical of a tropical monsoon climate with a warm and humid climate. The temperature is comparatively stable throughout the year and the relative humidity is always high. The mean monthly temperature ranges from 24^{o}C in July to 26^{o}C in January while in northern Nigeria, the observed maximum temperature is between 38^{o}C- 42^{o}C. Rain falls in most months of the year, but peak rainfall is observed between June an average of 125 rainy days in each year (Bandyopadhyay et al., 2012; www.weather-and-climate.com/Nigeria). The soil and vegetation of the Sub- Saharan Africa is heavily impacted by variation in climatic conditions (changes in temperature, rainfall and humidity) (Omogbai, 2010).

5.6.2. Nigeria soil sampling and sample types

Basic soil classification in Nigeria uses the USDA soil taxonomy (1975) as well as the FAO/UNESCO (1988) classification system. On the basis this taxonomic classification and international soil classification system coupled with FAO Nigeria soil map, major soil types in Nigeria were identified (Harpstead, 1973). On the field, physical characteristic assessment of soil was undertaken, including physical colour matching and textural feeling in comparison to stated soil on the Nigeria soil map. Different soil types in Nigerian including ferralsol, nitisol, luvisol, acrisol, fluvisol, lixisol, regosol, arenosol, cambisol and gleysol (Nwachokor and Uzu, 2008) were sampled during the sampling campaign. Major soils types sampled from Nigeria and characteristics are highlighted in the Table 6.6.

Table 5.6. Principal Nigerian soil types and properties (Bationo et al., 2006; FAO,2014; http://www.fao.org/3/i3794en/I3794en

Soil types	Distribution in Nigeria	Colours	Characteristics (OM, Soil water, structure and texture)	Remarks
Gleysols	Akwa-ibom, Delta, Ondo, Taraba, Benue, Bauchi, Plateau	Reddish brown/ yellow, Wetness	Mineral soils, Reducing gleyic properties. Suitable for growing rice, naturally deficient of oxygen. Presence of Fe and Mn oxides	Groundwater affected
Fluvisols	Delta, Lagos, Niger, Kaduna, Akwa-ibom	Yellow/ brownish	Alluvial soils, Young soils found in temporary flooded sites. Good for growing swampy rice	Presence of stratified fluviatile sediments
Acrisols	Sokoto, Katsina, Kano, Kebbi, Enugu, Kaduna, Benue, Niger	Very deep, reddish, pale yellow	Poorly drained, High leaching Highly susceptible to erosion, low mineral, high water holding capacity, high clay content in subsoil. Strongly weathered soils, they are acidic soils liming requirements	High level low activity clay mineral, paedogenic process
Ferralsols	Zamfara, Kaduna, Zaria, Rivers, Delta, Akwa-ibom	Red or yellow colour	Low silt to clay ratios, Well drained. Good structure, low profile, low water holding capacity, low nutrients. Good for deep rooted crops. High in kaolinitic clay. high in quartz and hydrated oxide, low Ca and Mg	Dominant kaolinite and oxides
Nitisols	Akwa-ibom, Lagos, Delta, Kogi, Edo, Bayelsa, Oyo, Abuja, Niger, Ondo, Kwara	Dark red or yellow	Deep well drained soil High in Fe and kaolin, Rich OM and clay content, good soil structure, high fertility, high water holding capacity	Low activity clay, P-fixation, strongly structured with many Fe oxides

Table 5.6 continued

Soil types	Distribution in Nigeria	Colours	Characteristics (OM, Soil water, structure and texture)	Remarks
Luvisols	Kwara, Oyo, Kano, Bauchi, Abuja, Osun, Kogi, Zamfara	Grey-brown	Contains variety of alluvial materials Distinct clay differentiation, mainly high activity clay, contains high silt. Permits deep rooting perennial crops and resistant to erosion Crops like wheat, sugar, beets can be cultivated High base saturation, high CEC	High activity clay high base status
Cambisols	Kwara, Abuja, Gombe, Kano, Kaduna	Mostly brownish intense dark colour	Rich OM, Weak and moderately develop soils. Medium to fine texture, well developed horizon evident in colour structure and clay content High water holding capacity, retains good amount of nutrient. Dominated by kaolin Permits deep rooting perennial cops	Moderately developed
Lixisols	Abuja, Oyo, Kano, Kogi, Edo	Red or yellow	Low capacity to retain nutrients, high amount of OM. Highly saturated with cations. Easily depleted of nutrients	Low activity clay high base status
Arenosols	Zamfara, Lagos, River, Kano	Deep sandy soil brown	Weakly structured, susceptible to erosion, Mostly sandy soil. Low water holding capacity, low nutrient content and high leaching. Rich in quartz and sedimentary rocks and contains Kaolin. Poor soil for agricultural use but may permit permanent crops	Sandy
Regosols	Ibadan, Zaria, Adamawa	Brown	Weakly developed soils require irrigation. Rich in unconsolidated coarse fragments. Poor soil for agricultural purpose but useful for livestock grazing, acidic found in arid and dry location	No significant profile development

Samples of the ten soil types listed in Table 5.6 were collected during the research campaign in Nigeria. At every location, five spot sample of undisturbed soil were collected. As much as possible sampling involved making 25m by 25m squared measurements and within the squared area five soil samples were collected. See figure 4.3C (ISO-10381-1. 2002) highlighting soil sampling approach. This approach ensured uniform soil samples were collected at every sampled location. According to IAEA. (2009), 0-10cm soil depth, should be considered soil zone for pastures for soil-to-plant transfer sampling. Consequently, 0-10cm depth was considered because radiocaesium is strongly retained on the surface topsoils for a long time after deposition and this zone is the rooting zone for most crops (Takeda et al., 2015). The five samples were thoroughly mixed together, and one representative soil sample retained for subsequent analyses. To ensure sampling variability, the next sampling point was about 1-2km away from the previous sampling point. Three representative samples of each principal soil types were collected and a total of 48 soil samples were obtained for the analysis. Some principal soils were sampled from more than one location. Soils were air dried for 2-3 days and sieved with a 2mm sieve. Fifty grams of each sample was enclosed in a sampling bags and taken to the controlled lab in SCK•CEN to determine the radiocaesium interception potential (RIP). Principal soil samples collected were representative soil type and covered the geographical spread of Nigeria. On the spot or field assessment of soil physical characteristics (soil colour inspection, soil textural feeling in between fingers) were performed and corroborated with the soil types indicated on the FAO-UNESCO soil map. Figure 5.1 shows the map of Nigeria and the locations sampled.

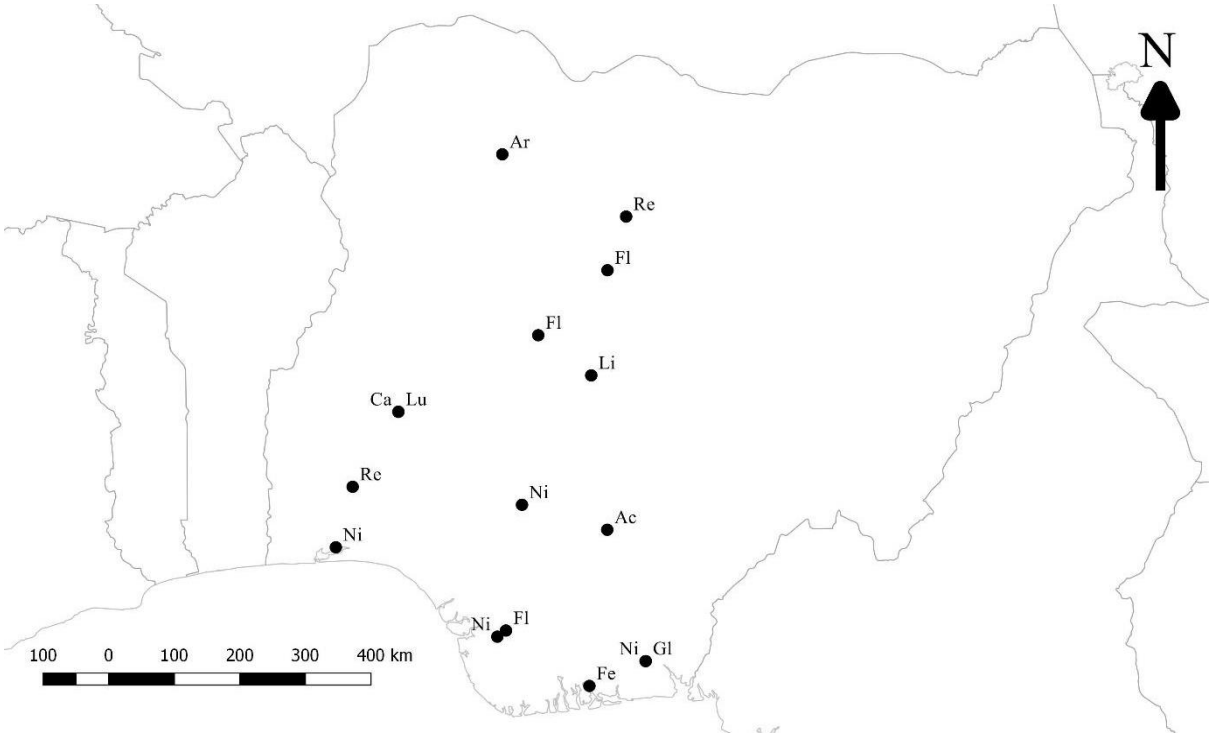

Figure 5.1. Locations where soils for RIP measurement were collected.

The codes represent the first two letters of each soil types (Ar=arenosol, Re= regosol, Ca= cambisol, Fl= fluvisol, Ni= nitisol, Li= lixisol, Ac= acrisol, Lu= luvisol, Gl= gleysol, Fe= ferralsol). The large dotted signs indicate locations where soil samples were collected.

5.6.3. Soil chemical analysis

Soil pH was determined using a pH meter and measurement was undertaken in a supernatant suspension of soil to water ratio of 1:1 (Udo & Ogunwale, 1986). Twenty grams of the fresh soil sample was weighed into 50 ml beaker and 20ml of distilled water was added. The solution was stirred with a glass rod and allowed to stand for 30minutes. The electrode of the pH meter was inserted into the partly settled suspension and the pH was determined. The soil Cation Exchange Capacity (CEC) was measured by mixing excess sodium acetate (NaOAc) with the soil solution, stopper the tube and shake in a mechanical shaker for 2 minutes and centrifuge at 1600rpm for 10 minutes until the supernatant liquid became clear. The liquid was decanted, and the process repeated three times. The process resulted in exchange of the added sodium cations for the matrix cations. Subsequently, the sample was washed with isopropyl alcohol. To determine exchangeable cations (K, Ca, Mg, Na), ammonium acetate (NH_4OAc) solution at a pH of 7 was added which replaces the absorbed sodium with ammonium. The concentration of absorbed sodium and other cations were then determined by Inductively coupled plasma mass

spectrometer (ICPOES) (Chapman, 1965). To determine the soil organic matter content, the loss on Ignition (LOI) method was used. The LOI was determined by weight loss percentage of oven dried soil sample during ignition at 550^0C in a controlled muffle furnace overnight.

5.6.4. Soil textural analysis

Soil textures and particle sizes were determined by LA-960 Laser diffraction soil particle size analyser. This equipment offers high resolution, reproducibility and good accuracy-based that permits the analysis of particles over a large size range (Coulter, 2011). Hydrogen peroxide (30ml) was added to soils suspected to have high organic matter content to remove the organic matter component of the soil. About 0.5g of the soil was introduced into the particle size analyser and agitated for a few minutes. With the help of the ultrasound and laser diffraction, the sizes of the sample were determined (Eshel et al., 2004).

5.7. RIP measurement

The materials for the experiment include 48 dialysis membrane bags, 48 pots (250ml), four pots 2litres each and 160 glass vials(20ml). The RIP of soil (RIP_{soil}) was determined according to the procedure outlined in Wauters et al. (1996). The steps involved preparation of materials and reagents

5.7.1. Preparation of dialysis membrane bags, 250ml KCl solution, RIP solution & radiocaesium solution

Forty-eight dialysis membrane bags were prepared by making 19cm measurement of spectra /por molecular porous membrane tubing. The membrane tubing was dipped into water to enable a knot-tie to be made at one end. The membrane tubing was opened and allowed to dry. The 250ml solution (100mml/l of K), was prepared by weighing 1.864g of KCl and dissolving it in demineralised water in a glass beaker. The solution was transferred to a 250ml volumetric flask and filled with demineralised water to the mark. The radiocaesium interception potential (RIP) solution is a 2Litres solution containing 100mmol/l of Ca and 0.5 mmol/l of K and it was prepared by dissolving 29.702g of $CaCl_2.2H_2O$ in demineralised water in a glass beaker. The solution was then transferred to 2Litres volumetric flask and 10ml of concentrated KCl was added. The resultant solution (RIP solution) was filled up to the mark with demineralised water. The radiocaesium solution is a labelled radiocaesium solution with known activity concentration (the activity concentration is about $2x10^5$ Bq/l in 100mmol/l of Ca and 0.5 mmol/l of K. This was

obtained by weighing 150g/sample of a solution containing 100mmol/l of Ca and 0.5mmol/l of K and then add minimum volume of high activity radiocaesium solution to prepare a solution with an activity concentration around $2x10^5$ Bq/l.

5.7.2. Method

The membrane was placed in the dialysis vial and the weight of the dialysis membrane tubing taken dry. 1g of soil was added to each of the dialysis membrane bag and the weight was measured and recorded and 10ml of RIP solution was added to soils in the bag and the bags were closed at the other end. To the 250ml sorption assay pots, 150g of RIP solutions was added. The dialysis bag (containing soil and 10ml of RIP solution) was placed into each sorption assay bottle containing 150g of RIP solution and this was shaken in an end over end shaker, at room temperature for 8hrs. Afterwards, the supernatants were discarded.

To each bottle, 150g of fresh RIP solution was added and the bottles were loaded again over an end to end shaker and shaken at room temperature for 16hrs. The supernatant (which contains impurities including ions that are initially present in the soil) was discarded. The pre-equilibration of the soil was repeated with a solution containing 100mmol.l^{-1} of Ca and 0. 5mmol.l^{-1} of K (that is the carrier free RCs - ^{137}CsCl solution for which its molarity was known) and the bottle were loaded over an end- to- end shaker, at room temperature for 24hrs. The weight of the vials was measured empty and measured with the supernatants added. Four vials with the initial labelled solution were prepared in the same way and the activity of the labelled solution in Bq/g solution was determined. In each of the four 2 litre pots, 1900ml of RCs solution was required to be contaminated with 0.427 ml of caesium. The activity concentration of RCs in each measured vial that contains the supernatant was then determined. Radiocaesium solution after equilibration was measured using NAI (TI) gamma counter (1480, wizard 3" PerkinElmer).

5.7.2.1. The principle of KD determination method

The RIP was determined using the principle of the K_D determination, which involves a known mass of soil being pre-equilibrated with a solution of 100mmol.l^{-1} of Ca and 0.5 mmol. l^{-1} of K. The solid-liquid coefficient (K_D) value is calculated from the ratio between the concentration of RCs (^{137}Cs) in the soil to that in the solution (L/kg). This value is used to calculate RIP (mmol/kg).

RIP, therefore, is the value of the product of the K_D and the potassium concentration represented as M_k (mmol. l^{-1})

$RIP = K_D * M_k$

where RIP is the Radiocaesium Interception Potential and M_k is the K^+ concentration in the equilibrated solution. The ^{137}Cs concentration of the original soil sample before spiking with radiocaesium was measured by NAI gamma counter. K_D = The solid-liquid distribution coefficient (K_D) is expressed as (Bq/g in soil)/ (Bq/ml solution), M_k =0. 5mmol.l^{-1}

5.8. Statistical analysis

R statistics was used to compute correlation coefficients among soil parameters and using multiple regression analysis to predict relationship between RIP_{soil} in relations to other soil parameters. The climatic conditions in the tropics favours high rate of disintegration (mineral soil components including OM) such that the formation of finely weathered mineral soils such kaolin is enhanced. Dioctahedral micaceous clay are known for selective adsorption of caesium ion (Francis and Brinkley, 1976, Bouwer et al., 1983). Dominant Nigerian soils, kaolinites express weak adsorption for caesium ion, and these may have resulted to the low RIP values recorded. However, the range from Nigeria soil is higher than RIP reported by Rigol et al., 1999 and comparable with those reported by Cremers et al. (1990). Rigol et al. (1999) experimented on four organic soils obtained from Russia (150km and 200km north of Chernobyl and from Obninsk and Birnie in Scotland which were mainly histosol, fulvic/ humic and peaty podzol (Rigol et al., 1999). Table 6.4b compares RIP across different literatures and the current study. The highest RIP values were observed with fluvisols and lowest values recorded with acrisols. Figure 5.7a presents the RIP mean in different soil types sampled from Nigeria.

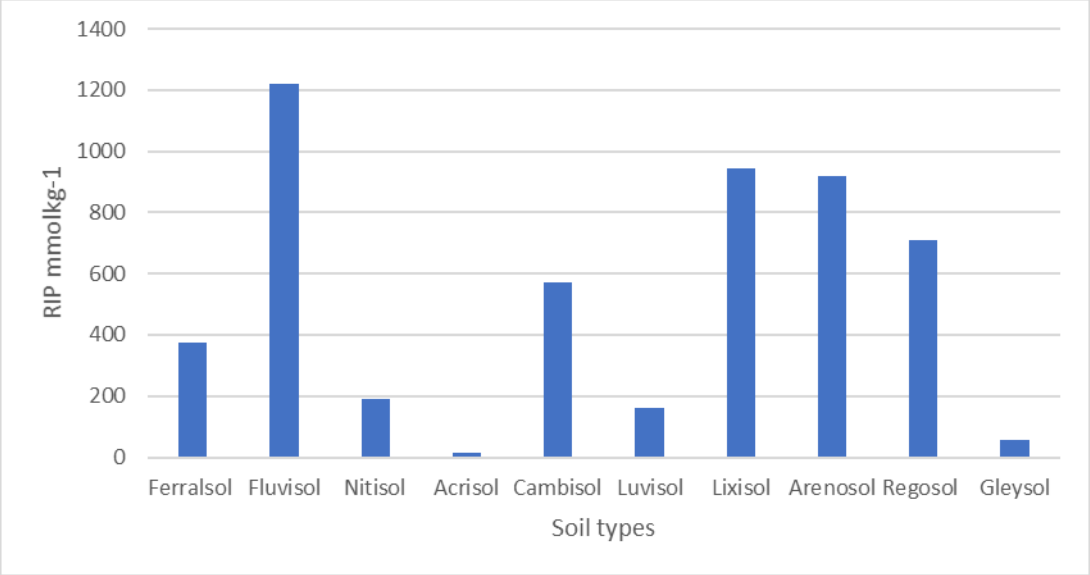

Figure 5.7a. Comparing Nigerian soil types and RIP values

Table 5.8a. The Nigerian soil properties (mean and standard deviation (SD) (mean ±SD) of the different soil types.

Sample	Ferralsol	Fluvisol	Nitisol	Acrisol	Cambisol	Luvisol	Lixisol	Arenosol	Regosol	Gleysol
n	3	6	12	3	3	3	3	3	6	2
Sand (%)	80.0±7.5	66.7±6.8	68.3±3.1	57.5±2.5	71.7±1.4	50.0±17.3	75.8±2.9	70.8±1.4	73.3±2.0	65.0±0.0
Clay (%)	20.0±7.5	33.3±6.8	31.7±3.1	42.5±2.5	28.3±1.4	50.0±17.3	24.2±2.9	29.2±1.4	26.7±2.0	35.0±0.0
pH in H2O	9.4±0.4	5.6±0.1	5.4±0.7	5.3±0.1	6.3±0.0	8.5±0.3	8.3±0.12	6.2±0.0	6.5±0.3	5.0±0.7
Ca (cmolc/kg)	15.3±6.8	5.7±7.8	0.4±0.2	7.3±9.6	12.9±10.9	13.0±7.3	10.8±8.7	0.2±0.2	5.6±7.2	0.4±0.1
Mg (cmolc/kg)	14.7±15.8	0.9±1.2	0.1±0.1	13.9±18.5	1.0±0.8	0.8±0.5	27.9±36.2	0.2±0.1	9.9±19.0	0.1±0.1
K (cmolc/kg)	7.3±10.6	0.1±0.1	0.1±0.1	8.1±11.9	0.1±0.0	0.1±0.0	22.7±33.9	0.1±0.0	6.7±13.9	0.1±0.0
CEC (cmolc/kg)	9.9±12.7	1.4±1.1	7.8±11.6	10.5±14.7	2.6±1.0	1.1±1.0	28.8±38.2	1.9±0.5	69.4±50.0	46.7±9.2
OM (%)	3.7±3.0	1.0±0.2	2.5±2.1	0.2±0.1	0.6±0.1	0.3±0.1	0.6±0.0	0.5±0.1	0.5±0.2	1.0±1.0
RIP mmol/kg	374.8±205.7	1218.7±1298.3	191.0±165.3	16.2±1.9	572.5±29.6	162.3±109.7	942.6±61.3	919.0±41.6	709.9±488.6	57.8±14.1

Table 5.8b. Comparisons between RIP from different studies (Rigol et al., 2002; Vandebroek et al., 2012)

Source	Locations	Soil types	n	O.M. [%]	Clay [%]	RIP [mmol kg−1]
Cremers et al., 1990	Europe	organic soils	8	23–88	3–23	65–2450
Sweeck et al., 1990	Belgium	plant spinach	12	0.5–8.6	0.5–33	67–4890
Valcke, 1995	Belgium, Cumbria, Ireland, Scotland	peat podzol	33	7–97	–	7–9199
Smolders et al., 1997	Belgium	plant spinach	30	2–28	0.5–36	54–5861
Waegeneers et al., 1999	Belgium, France, Germany, Spain and UK	Podzol, Luvisol, fluvisol	88	2–28	0.5–40	50–11 200
Rigol et al., 1999	Russia and Scotland	peaty, podzol	4	69–97	–	7–520
Sanchez et al., 1999	Wales, North England Scotland		23	12.6–96.5	2–57.6	5–6545
Yera et al., 1999	Belgium, France, Germany, Spain and UK	Podzol, luvisol and fluvisol	5	1–4.5	4.9–16.4	443–2732
Delvaux et al., 2000	Belgium, Austria, Germany, Italy, Ireland, Switzerland	histosol, leptosol, regosol, luvisol, cambisol, podzol	47	0.5–96	00.7–66	13–4861
Sanchez et al., 2002	Wales, North England Scotland	Gleysol, histosol, peat and cambisol	53	1.9–96.5	0.5–93.8	5–6545
Gil-García et al., 2009	Compilations		30	0.2–9.4	6.3–52.4	179–7000
Vandebroek et al., 2012	Worldwide	Podzol, regosol, vertisol, nitisol, luvisol, fluvisol, gleysol, ferralsol, arenosols, cambisols	88	0–19.5	0–84	1.8–13 343
This study	Nigeria	ferralsol, fluvisol, gleysol, nitisol, lixisol, arenosol, cambisol, acrisol, regosol	48	0.2-7	13-60	14.1-2466

5.9. Results

The results of the radiocaesium interception potential (RIP) of the Nigerian major soil types and soil physicochemical properties were presented in table 6.8a. No specific pattern has been detected from the results presented. According to Vanderbroek et al. (2012), RIP values below 2000mmol/kg can be classified as 'low'. Majority of the RIP results from Nigeria soils were below 2000mmol/kg except for fluvisol with RIP values of 2403mmol/kg. The second table 6.8b shows the comparisons of Nigerian RIP values with those of other literatures from other parts of the world. RIP values from this study were higher compared to RIP values obtained by Rigol et al. (1999) which experimented low illitic Mediterranean soil, low in OM as well as Russian soil (Low OM, CEC<5% clay fraction & high peat content). However, RIP values from this study were comparable with RIP values from Cremer et al., 1990 and Yera et al., 1999 (European soils, from Belgium, France, Spain, Germany, and UK) within a similar order of magnitude and the clay mineral were kaolin and mixture of illites and smectite (Yera et al., 1999). From table 6.8a the mean values of CEC, OM, pH, % clay for the different soil types are also presented. Both tables 5.8a and 5.8b would be discussed below.

5.9.1. Discussion of results

The influence of organic matter on radiocaesium transfer was evaluated by examining the relationship of organic matter and RIP in the different soil analysis using statistical regression. Fan et al. (2014) stated that OM can reduce RIP to a certain extent but the results from the study did not suggest OM matter has relationship with RIP. Similarly, no relationship was observed with other parameters such as percentage clay content, CEC, K^+ and pH. The log of each parameters was checked again evaluated with RIP and the result was not different from the initial results. Therefore, the variation between RIP and soil properties compared to reports from Fan et al., 2014, showed that difference may be due to other factors especially the clay mineral types. According to Vandebroek et al. (2012), RIP values of various kind of soils are closely associated with soil mineralogy. Further to this, Vandebroek et al. (2012) suggested that kaolinite and montmorillonite have small RIPs while vermiculite and illites usually present larger RIP values. The result of this research agrees with this report of Vandebroek et al. (2012) and as earlier established, the dominant mineral for the Nigeria soil is kaolinite (Igwe et al, 1999). Comparison of RIP from Nigeria to other RIP from other part of the world in table 6.8b, showed Nigerian soil RIP were relatively low which may likely be

attributed to the dominant kaolinitic clay mineral in Nigerian soils (Vandebroek et al., 2012). RIP compiled from literature across different geography did not conform to a uniform pattern, an indication that ^{137}Cs sorption may not be based on reference soil group classification, especially when the FAO international soil classification were not based on clay mineralogy but agronomical criteria which do not explain the sorption behaviour of RCs. Therefore, clay mineralogy is the major factor that controls caesium sorption capacity in soil (Maes et al., 1999; Joussein et al., 2004; Vanderbroek et al., 2011).

5.9.2. Multiple statistical analysis

Both tables 5.8c and 5.8d show the results of the regression analysis of RIP and soil properties.

Table 5.8c. Summary statistics of linear regression analysis of Nigerian RIP soil sample.

Variable	**Intercept**	**R-Sq**	**R-Sq (adjusted)**	**Df**	**P- value**	**F-value**
pH (water)	11.16	0.04	0.02	45.00	0.20	1.75
CEC (cmolc/kg)	380.35	0.02	0.00	45.00	0.31	1.05
Mg (cmolc/kg)	542.37	0.00	-0.02	45.00	0.89	0.02
%Clay	685.46	0.07	0.06	45.00	0.01	8.07
%Sand	-1562.31	0.18	0.17	45.00	0.00	10.09
K (cmolc/kg)	536.28	0.00	-0.02	45.00	0.97	0.00

Table 5.8d. Multiple regression analysis summary statistics.

Variables	Intercept	R-Sq.	R-Sq. (Ad)	Df	P- value	F-value
OM+CEC	582.22	0.05	0.01	44	0.29	1.27
K+CEC	483.66	0.02	-0.02	44	0.58	0.56
CEC+Clay	1452.03	0.18	0.15	44	0.01	4.99
K+ Clay	1521.12	0.19	0.15	44	0.01	5.04
K+CEC+Clay	1468.70	0.19	0.13	43	0.03	3.36
All variables	1433.16	0.32	0.20	39	0.02	2.68

Using R statistical package, the correlation and regression analysis of RIP with soil properties was undertaken to understand the relationship of a combination of soil properties on radiocaesium interception potential (RIP). The results of the individual factor analysis are presented in Table 6.8c. The Regression Analysis (RIP and CEC of the Nigerian soil) with (adjusted R-squared value = $1.17X10^{-3}$, DF=45, p value =0.31 F-statistic: 1.05) and the F-statistics shows no significant difference between RIP and CEC. Similarly, the analysis of RIP and K^+ with (adjusted R-squared value = -0.02, DF=45, p value =0.97 F-statistic: $1.4X10^{-3}$) shows no relationship between K^+ and RIP. For %clay analysis (adjusted R-squared value=0.06, DF=45, P value= 0.01, F- value 8.07), RIP was negatively correlated (-0.42) with percentage clay content. RIP value is not strictly related to the clay content of soil (Fan et al ., 2014) and the reason why some soils (including Gleysols and Acrisols) even with their high clay content(35% and 43% respectively), possible that these soils do not contain illitic minerals that contribute to a large RIP, may be the reason for their small RIP shown in table 5.8a. The relationship of RIP with clay may be due to the composition of the clay minerals rather than percentage clay of the soil (Fan et al., 2014). However, with sand, there was a contrast as RIP showed a weak relationship sand. The regression analysis (adjusted R-squared value = 0.17, DF=45, p value =0.003 F-statistic: 10.09) showed an adjusted R- squared value of 17% which suggested a gradual increase in RIP as the percentage of sand in the soil particle increases. This result is supported by Waegeneers et al. (1999) who found a correlation between RIP

and percentage sand with significant r value. However, Vandebroek et al. (2012) found a negative RIP correlation with sand).

RIP does not show strong relationship with any of the soil properties evaluated and this led to evaluation of multiple factors effect. Multiple regression analysis was computed to understand the effects of combined variables on the RIP. The results of the multiple regression analysis, involving the combination of variables (Sand, Clay, OM, pH, CEC) showed slight improvement in relationship between RIP and combined soil properties. The influence of all parameters (Adjusted R-Squared value of 0.2038) was higher than single factor effects. The R-Squared value also increases as the number of factor combination increases. Surprisingly, certain soil parameters which empirically were suggested to control RCs adsorption such as %clay, OM, CEC did not appear to show any relationship or of negligible impact. The geological origin of the soil and especially the mineralogy were the most important intrinsic soil characteristics which controls RCs retention in the soil. This assertion agrees with Waegeneers et al. (1999) and Vandebroek et al. (2012) that in considering large spatial scale, attention should focus on soil group and region and then other categories.

5.10. The revised Absalom models

Recent research work has emphasised the need for critical evaluation of the Absalom2001 model structure (Crout et al., 2009, Kimmins et al., 2008, Cox et al.,2006, Anderson, 2005). Conceptual simple method to evaluate the model structure based on reducing the model and replacement of variables with quantities which are constant was undertaken by Crout et al. (2009). The reduced model was then used to predict observations and compared with the original model to test the importance of the replaced variable in the model (Bernhardt, 2008). Crout et al. (2009) used the same data as Absalom2001 to demonstrate this method and suggested that Absalom2001 was over-parameterised and required to be simplified. This process led to a small improvement in the model's predictive performance (Tarsitano et al., 2011). However, more extensive data (including grass, wheat and barley) were introduced to enable a wide range of plant types and an extended radiocaesium contact time. The model structure was revised and evaluated using a subset of the available data not used for the model parameterisation (Tarsitano et al., 2011) which included independent radiocaesium transfer data for barley (n=71) covering contamination time between 1.2-10 years with

transfer factor ranging from (0.001-0.1). The model test accounted for 52% of observed variation in log transfer factor (Absalom et al., 2001).

5.10.1. Application of model to Nigerian data

The revised Absalom(X) model was applied to the Nigerian RIP soil data and evaluation of the model was done using concentration ratios of stable elements obtained from case study locations in Nigeria. Grass, barley and wheat data were used in the model and parameters values have been assigned to each plant. In the model application, parameter values for grass (a_1= 3.1) were used and parameter estimates were made by fitting the model with the input data using excel. The input data include soil physical and chemical parameter data from a total of 48 Nigerian soil (obtained from undisturbed vegetation at least for 10yrs). Model performance was evaluated using four statistical criteria including Nash and Sutcliffe (NS), root mean squared error (RMSE) criterion, total sum of square and the mean absolute error and model fit was tested using linear regression line of best fit (Myung, 2000). The mean absolute error (MAE) is the average absolute deviation between predicted and observed values. MAE of 0.03 was estimated between model prediction and site-specific measurements used for the model evaluation. This implies that the average model prediction was 0.03 off the actual values. MAE was calculated using the equation below

$MAE=1/N\sum i=1/N*(|Oi-Pi|)$

They both give values between 0 to infinity.

The prediction sum of square (PSS or PRESS) is used in regression analysis as a cross validation to provide a summary measure of the fitness of model to data that were not used in the model. It is an estimation of the sum of squares of all resulting prediction errors. It was estimated using the equation below

$PSS=\sum i=1N|Oi-Pi|^2$

The Nash and Sutcliffe (NS) Criterion, 1970, given by the equation below was used to assess model performance.

$NS=1-\sum i=1N(Oi-Pi)^2/\sum i=1N(Oi-\bar{O}i)^2$

Where N represents the number of data points and P and O are the predicted and observed (observed is same as site specific radiocaesium CRs. When NS=0 indicates model performs as well as the mean of the data while NS=1 suggest a good match between model and data and NS with negative value indicating the observed mean is a better predictor than is the model.

The closer the NS value is to 1 the better the model efficiency and more accurate the model is. Essentially, values between the threshold (0.5 < NS < 0.65) would suggest good performance of the model. The robustness of the model is indicated by a significant test of the NS and the probability of obtaining NS greater than the threshold. However, in this study, the NS value of 0.64 was obtained, suggesting that the Absalom model predictions were very good. At such model may be applicable to Nigeria and SSA environment.

5.11. Method description

The Absalom model was applied using constants values from the model parameter as well as measurements made from research sampling in Nigeria. These values were applied to sets of function derived for the model to determine transfer factor for grass. Estimation of concentration factors were made using the equation below

$$\text{Log (CF)} = -a_1 - a_2 \log (M_k) \quad \text{.....equ 1}$$

Where $a_{1=}$ 3.1 and a_2 1.8. These are the constants defined within the Absalom X model for deriving transfer to grass (Tarsitano et al., 2011).

Input values were substituted to estimate other variable parameters in the model which includes soil solution potassium concentration (M_k), radiocaesium activity concentration in soil (Bql^{-1}), whole soil labile radiocaesium distribution coefficient (K_D Lkg^{-1}) and ultimately Transfer factor (TF). The input variables used include $K_x$soil, (whole soil exchangeable potassium concentration ($Cmolckg^{-1}$)), Soil pH, and gravimetric clay content (gg^{-1}). The scheme of calculations and model parameter equations are given in figure 5.10a.

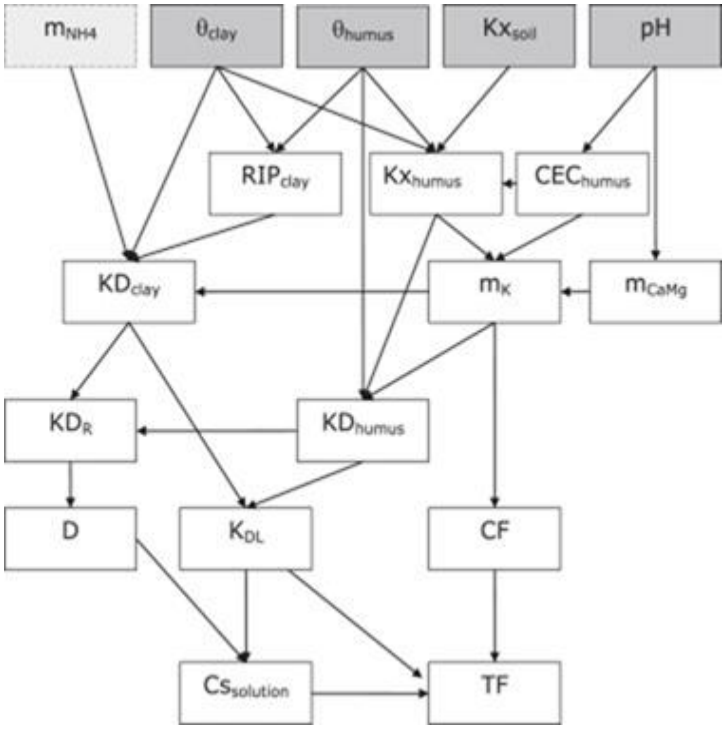

Figure 5.10a. The Absalom model (Tarsitano et al., 2011)

The function below was used to estimate the dynamic factor which describes the changes in labile radiocaesium with time. The time, 10 years, was assumed as the minimum fallow period of undisturbed vegetation. The time (t) was converted to hour equivalent (8760 hours)

D = exp (-kfast × t) ……equ 2

Where K_{fast} is a constant with a value =0.0019 and t has previously been defined

K_D clay was estimated using the equation below, where the molarity of ammonium ion was assumed to be zero (Tarsitano et al., 2011), a_7 was a constant RIP^{clay} and alpha clay were both obtained from soil analysis results

$$K_D^{clay} = \frac{RIP^{clay} \times \theta^{clay}}{m_K + a_7 \times m_{NH4}}$$ ……equ 3

K_{D1} was determined with equation 4 as K_{Dmin} tends to zero (Tarsitano et al., 2011), and $K_D$clay obtained from equation 3

$$K_{D1} = K_D^{clay} + K_{Dmin}$$ ……equ 4

Soil solution potassium concentration (M_k) was estimated using the equation below, K of soil and alpha clay were obtained from Nigerian soil data while the alpha humus was assumed to be zero

$$m_K = \frac{K_x^{soil}}{\alpha\theta^{humus} + \beta\theta^{clay} - \gamma K_x^{soil}}$$ ……equ 5

Thereafter, the $\log_{10}RIP^{clay}$ was calculated using the function given below where the values of a9 and a8 were both constants (Tarsitano et al., 2011)

$$\log_{10}(RIP^{clay}) = a_9 - a_8 \frac{\theta^{humus}}{\theta^{clay}}$$ ……equ 6

Finally, transfer factor (TF) was determined with equation 7

$TF = (CF / K_{DI}) \times D$…… equ 7

Where TF refers to transfer factor (dimensionless), D is the dynamic factor which describes the changes in labile radiocaesium with time. CF is the concentration factor for plant to soil solution radiocaesium concentration (L/kg), K_{DI} is the whole soil labile radiocaesium distribution coefficient (L/kg) and M_k represents concentration of K^+ in soil solution. Results of parameter inputs are presented in appendix 14. Comparison of predicted TF and actual TF from SSA data is illustrated in figure 5.10b.

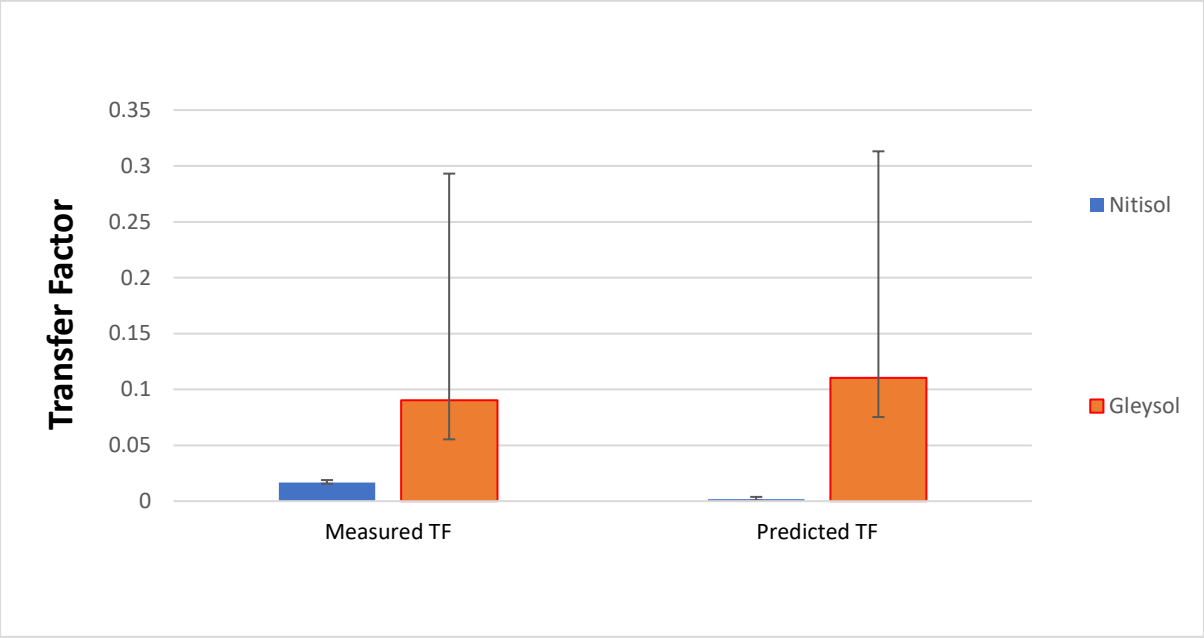

Figure 5.10b. Comparison of predicted transfer factor (TF) values against measured transfer factor (TF) values

5.12. Discussion

Figure 5.10 compared the mean Absalom predicted TF with mean transfer factors obtained from site specific 1 in Nigeria. Nitisols parameters obtained during the determination of soil RIP (Geregu) were applied to the model. Predicted transfer factor (TF) were compared with measured transfer factor for nitisol from Geregu (this measured TF data were for grass from Geregu and were not applied to the model). The mean of the measured transfer factor (1.67E-02) was higher by an order of magnitude compared to the mean of the predicted transfer factor (1.66E-03). Similarly, the major soil types in Itu, was gleysol. RIP gleysol data from Itu were applied to the model and predicted transfer factor were compared with measured gleysol transfer factor from Itu. The results of the mean measured transfer factor (0.09) was comparable to the mean of the Absalom predicted transfer factor (0.11 for gleysol in Itu. The predicted results in the context of transfer factor showed extremely good agreement and suggests that the Absalom model could be applied to the SSA.

5.13. Conclusion

Radiocaesium Interception Potential (RIP)in Nigeria soils has been determined. The range of RIPs of the Nigerian soils have been compared with range of RIP reported from the literature. The RIP from the Nigerian soils was generally low compared to values reported from other studies. The implication of this is that transfer of caesium may likely be higher for SSA which agrees with results presented in chapter three and four of this study. Essentially, this would imply that there is more potential for caesium contamination of the human food chain in SSA. In other words, the SSA environment (soil properties and prevailing climatic conditions) are more vulnerable or susceptible to caesium contamination of the human food chain. Therefore, this study is important for emergency preparedness and responses towards remediation of likely effects of caesium contamination. Absalom model has been applied and model performance was good. The model statistical performance validation using Nash and Sutcliffe yielded (0.64). An indication that the model performed very well for the Nigerian data.

6. GENERAL DISCUSSION/SUMMARY CONCLUSIONS

6.1. Introduction

This chapter will discuss the major findings and the scientific contribution of this research. It will discuss the application of both the ERICA and Absalom model to data from Sub-Saharan Africa and highlights some of the implications of the research findings. It will discuss the maintenance of the Sub-Saharan Africa database (SSAD). It will make recommendations on future directions and finally establish logical conclusion based on research findings.

6.2. Main findings

This thesis provides an in-depth insight into radionuclide transfer to the human food chain and non-human biota (wildlife) in Sub-Saharan Africa (SSA). In the case of human food chain, the knowledge of radionuclide transfer is critical to human health in terms of contamination, monitoring of releases of radioactivity to the environment as well as environmental protection. Wildlife are an important protected component of many ecosystems and assessment of radiation impact on these non-human biotas has gained significant recognition over the last few decades (Wood et al., 2011). Detailed, systematic review of published and unpublished literature revealed a lack of data on the transfer of radionuclides. In all six databases reviewed for the development of the SSAD, transfer parameter data were recorded for 12 radionuclides including ^{238}U,^{235}U ^{234}U, ^{234}Th, ^{233}Th, ^{232}Th, ^{230}Th, ^{228}Th, ^{228}Ra, ^{226}Ra, ^{210}Po, ^{210}Pb for wildlife and most of the radionuclides were naturally occurring radionuclides. For food crops transfer parameters data were obtained for 8 radionuclides including ^{137}Cs, ^{226}Ra, ^{227}Ra, ^{228}Ra ^{229}Ra, ^{228}Th ^{232}Th and ^{238}U and except ^{137}Cs, other radionuclides were uranium and thorium isotopes. The transfer parameter database developed will provide data useful for environmental radiological assessment. Grass yielded single elemental replicates with a total of 102 n values for zinc (Zn) and lead (Pb) but for freshwater and marine organisms, fish produced 614 replicates for strontium. Evidently, the systematic review suggests a lack of data especially for several radioisotopes (including ^{133}I, ^{131}I, ^{90}Sr ^{241}Pu, ^{137}Cs, etc). Data has been extracted from total of 211 references to compile the Sub-Saharan Africa database (SSAD) compared to 523 references utilised in the development of the wildlife transfer

database (Howard et al., 2013; Copplestone et al., 2013) which seemed to be very good for SSA, because the 523 references came from different part of the world. The SSAD database comprised a total of 26,346 CRs (Terrestrial wildlife=3,764, Food chain= 14,168 and fresh & marine water=8,414) which appears to be a good contribution towards developing a robust transfer database. The mean of SSAD CRs were compared with transfer data from established international dataset (IAEA, 2009; IAEA, 2014) and variability of CRs for individual crop and wildlife were observed to range up to three orders of magnitude (Nisbet and Woodman, 2000). The reasons for the variability of CRs has been attributable to a combination of factors which include soil biological, chemical and physical processes, plant physiology as well as other external factors (including climate and human agricultural practices). How these factors influence transfer has been highlighted in chapter two. Other major findings of the study are discussed below.

6.2.1. Sub-Saharan Africa database (SSAD)

In chapter three transfer parameters for terrestrial wildlife from the IAEA publication were an order of magnitude higher compared to SSAD transfer parameters. However, for the food chain, SSAD CRs were an order of magnitude higher compared to IAEA values. Overall, the mean SSAD transfer parameter was higher (4 times) than the mean values of IAEA transfer. Similarly, for freshwater and marine wildlife IAEA CRs values were 1-2 order of magnitude higher compared to mean values of SSAD.

6.2.2. Concentration Ratios (CRs) for human food chain and RAPs

The mean CRs data from GERITU (Geregu and Itu) were slightly higher than the mean of the IAEA reported CRs. Concentration ratios between the two case study locations were compared for both RAPs and food crops. For RAPs (Between Geregu and Itu), the mean CRs of Itu was 1 order of magnitude higher than Geregu (approximately 3 times higher). For the food crops CRs values were the same order of magnitude, although Itu values were slightly higher than Geregu. Results of CRs compared across site specific data (GERITU), SSAD and IAEA revealed that site specific data and SSAD mean CRs were in the same order of magnitude, however, site specific CRs were 3 times higher than SSAD in food crops. Similarly, SSAD were 4 times higher than IAEA in the following order (GERITU>SSAD>IAEA).

6.2.3. Nigeria data and model application

The chapter six result showed that radiocaesium interception potential does not show any relationship with most of the soil properties analysed (clay, sand, soil pH, CEC, OM). The ERICA Tool was applied for dose assessment of the non-human biota (wildlife) and was used to assess the environmental impact of establishing the nuclear power plant in Nigeria. The results of the Tier 2 assessment confirmed there was no risk to the environment as the dose level were below the benchmark values($10\mu Gyh^{-1}$) and the risk quotient were less than one. The revised Absalom approach was applied to predict transfer factor for radiocaesium. The predicted values were comparable with measured transfer factor which suggests that the Absalom model applied well to the SSA data.

6.3. Implication for environmental protection and management

Successful characterisation and management of environmental risk, assessment of exposure and effects, coupled with decision making related to environmental effects of ionising radiation, depends on a system capable of predicting radionuclide transfer in the environment (Brown et al., 2008; Howard et al., 2008). The SSAD provides fundamental transfer data to enable environmental risk characterisation and radiation impact assessment for the region. Similarly, the results of this study will form a useful input to the International Atomic Energy Agency (IAEA) working group which is currently developing new programmes on the behaviour of radionuclides in arid environments (iaea.org/projects/emras/emras2).

Model application and validation using parameter data from this study has been undertaken both for wildlife and human food chain using ERICA tool and Absalom model respectively. Although model fit may not be a hundred percent however, available evidence from the results of model predictions reinforced confidence in the applicability of European model to Sub-Saharan Africa regions. The results also confirm the research aims that parameter values predominantly derived from European and North America data will be applicable to SSA.

6.4. Radionuclide transfer in SSA

There is an increasing commitment to the development of nuclear programmes in Sub-Saharan Africa. In Nigeria, the government has commenced plan on its nuclear power project and feasibility studies undertaken with two locations selected for the nuclear facility

construction. The nuclear power roadmap is aimed at generating 1000MW of electricity by 2020 and 4000MW by 2030 (Ejiogu,2013; http://www.world-nuclear-news.org/articles/iaea-helps-nigeria-plan-for-new-research-reactor). Similarly, in August 2019, the Ghanaian vice president confirmed a nuclear commitment and support towards construction and operation of Ghana's first nuclear power plant with both legal and regulatory framework to commence immediately (http://www.world-nuclear-news.org/Articles/Vice-President-confirms-Ghana-nuclear-commitment). Other SSA countries such as Niger, Kenya and Sudan have plans to develop nuclear power to improve energy security. As a result of the increasing nuclear commitments, radionuclide transfer must be assessed. This thesis will make huge contribution to knowledge in the area of environmental assessment of radionuclides transfer to human food chain and wildlife in Sub-Saharan Africa. Already the study has established the Sub-Saharan Africa Database (SSAD) of radionuclides transfer parameters. This is the first radionuclide transfer database to be developed for the region. This database is required to quantify radionuclides transfer to both human food chain and non-human biota. More so, in the course of the research work characterisation of radionuclides (stable elemental analogues) transfer at the planned location for the construction of nuclear power in Nigeria was undertaken. Site specific data were produced which provided the opportunity to assess potential impact and risks that may be associated with the construction of the nuclear plant. Risk impact assessment of the nuclear power plant has been undertaken using ERICA tool and the study can confirm there will be no impact on wildlife.

Furthermore, with the growing concerns and development of nuclear power in the region, there is a need to develop a robust system for the region that would ensure radiological information required for environmental impact assessment are readily available and to ensure systems are in place to determine risk impact of radionuclides transfer. The ERICA integrated approach will be an applicable approach for radionuclides transfer, effects and risk assessment for wildlife in the region (Brown et al,2008; Howard et al., 2008; Copplestone et al., 2013; Brown et al., 2016). This study also provided the first comprehensive transfer data on default assessment organisms (RAPs) for the region. Furthermore, the development of site-specific data provided transfer data which can serve as baseline radionuclide dataset for the planned nuclear power plant in Nigeria. In addition, radiocaesium interception potential (RIP) measurements have been determined for Nigerian soil and the first RIP data for the

Nigeria. This data is significant for the purpose for future emergency planning preparedness and response. The RIP data alongside soil physical properties will enabled spatially implementable model (Absalom model) to predict radiocaesium transfer factor for the region. Finally, database will be maintained online to encourage other researchers to provide data relevant to food chain and wildlife transfer and at such contribute to periodic update of the SSAD.

6.5. Future direction

By Assessing environmental radionuclide transfer in Sub-Saharan Africa, the present study provides the fundamental knowledge required to assess radiation impact on humans and wildlife in the SSA which set out the basis for environmental protection and management. The result findings highlighted important questions for which further researches are required to advance the knowledge of environmental radionuclide transfer in SSA. Firstly, is the area of the applicability of currently used assessment approaches to other geographical locations and in this case Sub-Saharan Africa. In chapter two, the review of the application of radiological assessment model was done. Very few of the assessment model have been applied to SSA. Further assessment of the applicability of currently used assessment approaches for implementation in Sub-Saharan Africa needs to be done. This would assess organisms from SSA including protected species, carefully matching protected species in SSA ICRP RAPs & ERICA Reference Organisms (ROs). It will help to identify protected species in SSA for consideration in the reference organism list for which transfer data is lacking as well as improve understanding to the full list of RAPs and ROs available in SSA, more research study is required. Secondly, further study to address data gaps in radionuclides transfer is required. the gaps that require further research include radionuclides transfer to freshwater and marine organisms to develop a comprehensive freshwater and marine database of radionuclide transfer in a whole range of organisms and radionuclides combinations for Sub-Saharan Africa is required. There is lack of data for radioisotopes for both human food chain and non-human biota for which data gap filling is required. Further research will address these gaps which would lead to a robust radionuclide transfer database for the region. Thirdly, the use of models to implement radiological approaches and to aid in decision making on contamination by radionuclides is critical. There is a need to further explore the use of predictive models to assess radiological releases (planned or accidental) of contaminations

(^{90}Sr, ^{137}Cs and others) and establish remediation and restoration responses for the Sub-Saharan Africa region as well as develop GIS-based vulnerability assessment for contaminations such as radiocaesium mobility in the environment and availability to crops in the Sub-Saharan Africa. Fourthly, naturally occurring radionuclides material (NORM) from industries and heavy metals that need to be assessed. There are several mining activities in Niger, Ghana, Nigeria, South Africa and many other countries in the region (Steenkamp and Clark-mostert, 2012) as well as oil exploration activities and other solid minerals extractions leading to releases of naturally occurring radionuclides and heavy metals. With huge legacy of contaminants from industrial activities in SSA, it is important for further research to explore the transfer of these elements to human food chain and wildlife. Finally, other research questions include field measurement and study on radionuclide dose exposures. Dosimetry study combined with transfer will give better understanding of exposure level and help to quantify risk, management environmental radiation effects and ultimately better decision. Consequently, the maintenance of the Sub-Saharan African database (SSAD) will continue even after the PhD thesis as a result of continuous update and further incorporation of transfer data especially in areas with limited datasets to produce a highly robust database.

6.6. Conclusion

In conclusion, Sub-Saharan Africa database (SSAD) of radionuclides transfer parameters has been developed and the research objective one has been accomplished. This database has been compared with currently available database from Europe and North America. Result revealed that transfer parameters within the SSAD are different from those of international database, although comparable in some food crops and wildlife species and with this, the second objective of the research was met. The developed SSAD for wildlife will be incorporated into the wildlife transfer database and the food crop database for SSA will be available for use in future update of international compilations of human food chain transfer parameters values. Furthermore, site specific transfer parameters at the two case study locations, Geregu and Itu, were determined for various stable elements and radionuclides, in line with the research objective three and has been incorporated into the SSAD to fill in the data gaps. Dose assessment of the potential impact of the nuclear power plant was undertaken using ERICA model. The dose assessment result confirmed that, potential discharges from the nuclear power plant will be negligible. Further assessment of the soil

radiocaesium interception potential was undertaken and RIP results from a Sub-Saharan Africa setting was compared to RIP from other parts of the world. The RIP of the Nigerian soil was low compared to RIP from other regions due to several factors highlighted in chapter five. Applying the Absalom model confirmed model applicability to an SSA setting and in the event of nuclear emergency planning and response situation. By studying environmental radionuclides transfer in Sub-Saharan Africa, the thesis provides key insights to transfer parameters in human food chain and wildlife in SSA. The insights gained on dose assessment and application of the Absalom model establish the aim of the research that datasets and models developed in Europe and North America may be applicable to the SSA. Together, the results present a significant advancement in international understanding of radionuclides and stable elements behaviour within the Sub-Saharan Africa and help to underpinning the development of a system of radiological protection as well as emergency planning within the SSA.

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APPENDIX

Appendix 1. Descriptive statistics for CRs of terrestrial wildlife (SSAD vs IAEA)

CRs of Terrestrial Wildlife (SSAD vs IAEA)

Wildlife	Environment	Elements	N	AM	ASD	GM	GSD	Min	Max
Amphibian	IAEA	Cr	6	2.74E-03	1.71E-03	2.34E-03	1.82E+00	1.31E-03	5.56E-03
	SSAD	Cr	26	1.31E-01	1.01E-01	9.04E-02	2.68E+00	1.23E-02	4.25E-01
	IAEA	Mn	6	3.59E-02	2.15E-02	3.13E-02	1.75E+00	1.63E-02	7.46E-02
	SSAD	Mn	26	1.82E+00	1.27E+00	1.31E+00	2.57E+00	2.07E-01	5.05E+00
	IAEA	Ni	6	5.83E-03	6.69E-03	3.60E-03	2.82E+00	1.40E-03	1.85E-02
	SSAD	Ni	6	8.84E-04	2.25E-04	8.60E-04	1.30E+00	5.70E-04	1.25E-03
	IAEA	Pb	6	1.55E-02	2.75E-02	5.79E-03	3.93E+00	1.96E-03	7.12E-02
	SSAD	Pb	26	2.96E-01	1.05E-01	2.76E-01	3.93E+00	1.23E-01	4.75E-01
	IAEA	Zn	6	8.62E-01	2.67E-01	8.26E-01	1.39E+00	4.97E-01	1.25E+00
	SSAD	Zn	26	6.33E+00	4.36E+00	3.36E+00	4.90E+00	1.23E-01	1.78E+01
Annelid	IAEA	Co	15	4.65E-01	3.67E-01	2.52E-01	4.36E+00	1.23E-02	1.10E+00
	SSAD	Co	5	1.59E-01	9.48E-02	1.37E-01	1.86E+00	5.66E-02	3.10E-01
	IAEA	Cr	12	1.92E-02	2.05E-02	1.24E-02	2.60E+00	2.87E-03	6.55E-02
	SSAD	Cr	16	1.20E-01	3.22E-02	1.15E-01	1.33E+00	6.14E-02	1.75E-01
	IAEA	Mn	12	5.58E-02	5.97E-02	2.13E-02	5.23E+00	3.34E-03	1.67E-01
	SSAD	Mn	15	3.38E-02	4.38E-02	1.39E-02	4.14E+00	1.62E-03	1.20E-01
	IAEA	Ni	12	3.01E-02	1.67E-02	2.67E-02	1.63E+00	1.31E-02	7.24E-02
	SSAD	Ni	21	5.17E-01	5.80E-01	3.53E-01	2.33E+00	1.04E-01	2.66E+00
	IAEA	Pb	12	5.98E-02	1.06E-01	3.24E-02	2.57E+00	1.01E-02	3.93E-01

Wildlife	Environment	Radionuclides	N	AM	ASD	GM	GSD	Min	Max
	IAEA	Zn	12	6.57E+00	3.96E+00	5.51E+00	1.89E+00	2.15E+00	1.52E+01
	SSAD	Zn	29	1.25E-01	8.13E-02	9.59E-02	2.37E+00	1.27E-02	3.77E-01
Arthropod	IAEA	Cr	5	9.49E-03	4.12E-03	8.64E-03	1.67E+00	3.92E-03	1.47E-02
	SSAD	Cr	15	1.60E-03	1.82E-03	1.12E-03	2.18E+00	4.40E-04	7.53E-03
	IAEA	Mn	6	1.86E+00	1.56E+00	1.19E+00	3.05E+00	3.76E-01	3.36E+00
	SSAD	Mn	15	1.62E-02	1.59E-02	1.17E-02	2.14E+00	5.65E-03	5.15E-02
	IAEA	Ni	6	2.70E-01	2.86E-01	1.00E-01	6.00E+00	1.74E-02	6.47E-01
	SSAD	Ni	15	2.12E-02	1.25E-02	1.76E-02	1.97E+00	3.11E-03	4.75E-02
	IAEA	Pb	6	1.02E-01	1.60E-01	4.51E-02	3.81E+00	9.42E-03	4.24E-01
	SSAD	Pb	18	8.94E-03	1.55E-02	2.90E-03	4.51E+00	3.50E-04	5.45E-02
	IAEA	Zn	6	5.14E+00	2.07E+00	4.78E+00	1.52E+00	3.14E+00	7.54E+00
	SSAD	Zn	15	5.98E-03	3.65E-03	4.67E-03	2.22E+00	1.20E-03	1.18E-02
Grasses	IAEA	Co	57	4.53E-02	8.76E-02	1.69E-02	4.34E+00	3.60E-04	5.63E-01
	SSAD	Co	30	2.54E-02	2.49E-02	1.42E-02	4.06E+00	2.50E-04	8.90E-02
	IAEA	Cr	13	1.51E-01	1.73E-01	7.98E-02	3.40E+00	1.12E-02	5.59E-01
	SSAD	Cr	61	1.13E-01	1.71E-01	5.04E-02	3.63E+00	8.37E-03	1.06E+00
	IAEA	Cs	52	3.49E-02	6.58E-02	1.67E-02	3.21E+00	1.16E-03	4.12E-01
	SSAD	Cs	7	3.27E-02	1.99E-02	2.84E-02	1.73E+00	1.63E-02	6.85E-02
	IAEA	Cs-137	1005	1.65E+00	2.76E+00	6.16E-01	4.57E+00	1.85E-03	3.65E+01
	SSAD	Cs-137	2	3.09E-01	0.00E+00	3.09E-01	1.00E+00	3.09E-01	3.09E-01
	IAEA	Cu	13	1.28E+00	1.27E+00	8.56E-01	2.51E+00	2.65E-01	4.40E+00
	SSAD	Cu	7	4.66E-01	3.73E-01	3.32E-01	2.58E+00	9.19E-02	1.06E+00
	IAEA	Mn	13	6.80E-01	5.60E-01	5.43E-01	1.90E+00	3.00E-01	1.91E+00
	SSAD	Mn	20	3.36E-01	3.58E-01	2.31E-01	2.26E+00	9.92E-02	1.30E+00
	IAEA	Mo	19	1.07E+00	9.20E-01	6.51E-01	3.22E+00	5.97E-02	3.25E+00
	SSAD	Mo	28	5.87E-01	8.91E-01	2.55E-01	3.84E+00	1.35E-02	3.56E+00
	IAEA	Ni	13	2.67E-01	2.62E-01	1.64E-01	2.98E+00	3.35E-02	9.39E-01

Wildlife	Environment	Radionuclides	N	AM	ASD	GM	GSD	Min	Max
	IAEA	Pb	13	1.08E-01	2.02E-01	3.00E-02	4.56E+00	5.84E-03	6.26E-01
	SSAD	Pb	102	7.30E-02	8.54E-02	4.48E-02	2.79E+00	3.42E-03	6.17E-01
	IAEA	Ra-226	252	2.09E-01	4.73E-01	2.67E-02	2.21E+01	3.00E-05	4.65E+00
	SSAD	Ra-226	21	8.08E-01	5.43E-01	6.77E-01	1.79E+00	2.93E-01	2.14E+00
	IAEA	Rb	55	1.53E-01	2.57E-01	6.12E-02	4.11E+00	5.32E-03	1.44E+00
	SSAD	Rb	7	5.97E-01	5.29E-01	4.58E-01	2.11E+00	1.97E-01	1.70E+00
	IAEA	Se	34	8.99E-01	1.36E+00	2.31E-01	8.17E+00	2.18E-03	5.40E+00
	SSAD	Se	1	4.51E-03	.	4.51E-03	1.00E+00	4.51E-03	4.51E-03
	IAEA	Th-232	27	1.06E-01	1.62E-01	3.49E-02	5.38E+00	1.63E-03	6.52E-01
	SSAD	Th-232	39	6.49E-01	5.48E-01	4.82E-01	2.21E+00	9.47E-02	2.37E+00
	IAEA	U	82	2.29E-02	3.22E-02	0.00E+00	1.02E+01	0.00E+00	1.64E-01
	SSAD	U	4	2.75E-02	1.96E-02	2.04E-02	2.73E+00	5.21E-03	4.87E-02
	IAEA	U-238	150	1.44E-01	5.32E-01	9.12E-03	1.61E+01	5.00E-05	5.54E+00
	SSAD	U-238	22	2.53E-01	1.29E-01	1.88E-01	2.85E+00	1.05E-02	5.30E-01
	IAEA	Zn	13	1.29E+00	1.09E+00	9.94E-01	2.08E+00	2.86E-01	3.81E+00
	SSAD	Zn	102	6.36E-01	1.01E+00	1.35E-01	1.31E+01	0.00E+00	5.58E+00
Grasses and Herbs	IAEA	Cs	16	5.79E-02	2.75E-02	5.12E-02	2.11E+00	2.04E-02	9.93E-02
	SSAD	Cs	17	2.47E-02	1.88E-02	1.91E-02	2.19E+00	3.76E-03	8.40E-02
	IAEA	Ra-226	30	1.11E-01	2.19E-01	3.08E-02	5.13E+00	1.84E-03	9.56E-01
	SSAD	Ra-226	12	1.69E+00	6.24E-01	1.57E+00	1.53E+00	8.29E-01	2.44E+00
	IAEA	Th-232	5	1.08E-01	1.45E-01	5.29E-02	3.88E+00	1.22E-02	3.60E-01
	SSAD	Th-232	12	4.58E-01	1.96E-01	4.22E-01	1.52E+00	2.45E-01	7.98E-01
Herbs	IAEA	Ce	106	1.65E-02	1.88E-02	7.50E-03	4.02E+00	5.00E-04	6.90E-02
	SSAD	Ce	9	6.21E-03	7.02E-03	2.06E-03	6.57E+00	1.40E-04	1.76E-02
	IAEA	Co	113	2.12E-02	1.75E-02	1.27E-02	3.23E+00	3.00E-04	6.30E-02
	SSAD	Co	82	1.14E-01	1.80E-01	3.42E-02	5.37E+00	6.60E-04	8.61E-01

Wildlife	Environment	Radionuclides	N	AM	ASD	GM	GSD	Min	Max
	IAEA	Cs	103	9.53E-02	2.75E-01	2.17E-02	4.49E+00	9.50E-04	1.34E+00
	SSAD	Cs	19	5.90E-02	3.05E-02	5.13E-02	1.75E+00	2.09E-02	1.26E-01
	IAEA	Eu	106	1.65E-02	1.72E-02	8.19E-03	3.79E+00	4.80E-04	6.51E-02
	SSAD	Eu	9	8.07E-03	7.43E-03	3.11E-03	6.84E+00	1.60E-04	2.04E-02
	IAEA	Mo	4	2.08E-01	8.52E-02	1.93E-01	1.62E+00	1.00E-01	2.80E-01
	SSAD	Mo	7	2.45E+00	2.14E+00	1.01E-01	3.58E+02	1.00E-05	6.02E+00
	IAEA	Ra-226	26	2.38E-01	3.23E-01	1.20E-01	3.20E+00	1.61E-02	1.33E+00
	SSAD	Ra-226	68	6.68E-01	4.93E-01	5.36E-01	1.93E+00	1.46E-01	2.14E+00
	IAEA	Rb	110	6.94E-02	7.15E-02	4.59E-02	2.58E+00	7.32E-03	4.53E-01
	SSAD	Rb	19	6.48E-01	3.08E-01	5.77E-01	1.68E+00	2.04E-01	1.22E+00
	IAEA	Sr	105	1.03E-01	4.39E-01	4.89E-02	2.12E+00	1.58E-02	4.50E+00
	SSAD	Sr	9	9.64E-02	1.03E-01	1.01E-03	4.32E+02	0.00E+00	2.39E-01
	IAEA	Th-232	41	5.86E-02	1.04E-01	1.66E-02	5.64E+00	2.20E-04	5.10E-01
	SSAD	Th-232	76	6.24E-01	3.77E-01	4.54E-01	2.90E+00	9.53E-03	1.58E+00
	IAEA	U	92	9.64E-02	1.09E-01	5.44E-02	3.24E+00	7.20E-04	5.87E-01
	SSAD	U	15	9.26E-03	1.21E-02	5.49E-03	2.72E+00	1.15E-03	4.80E-02
	IAEA	U-238	37	2.52E-01	6.07E-01	3.99E-02	5.77E+00	2.18E-03	2.79E+00
	SSAD	U-238	9	1.10E-01	1.86E-01	6.27E-03	2.00E+01	2.70E-04	5.13E-01
Mammal	IAEA	Pb	18	1.45E-02	3.33E-02	3.79E-03	4.47E+00	8.60E-04	1.42E-01
	SSAD	Pb	40	3.52E-03	1.89E-03	3.04E-03	1.77E+00	7.70E-04	1.07E-02
	IAEA	Se	40	2.36E-01	2.54E-01	9.19E-02	7.69E+00	1.70E-04	1.08E+00
	SSAD	Se	40	4.75E-03	6.83E-03	2.90E-03	2.31E+00	1.57E-03	3.60E-02
Tree	IAEA	Cr	27	6.23E-02	9.46E-02	3.10E-02	3.20E+00	3.73E-03	4.44E-01
	SSAD	Cr	7	6.01E+00	7.00E+00	7.63E-01	4.21E+01	3.50E-04	1.46E+01
	IAEA	Cs	24	8.32E-03	1.35E-02	3.59E-03	3.59E+00	5.10E-04	5.71E-02
	SSAD	Cs	3	3.18E-02	1.12E-02	3.06E-02	1.39E+00	2.42E-02	4.46E-02
	IAEA	Cu	27	6.29E-01	4.35E-01	5.26E-01	1.79E+00	2.26E-01	2.02E+00
	SSAD	Cu	3	5.65E-01	2.57E-01	5.24E-01	1.62E+00	3.18E-01	8.31E-01

Wildlife	Environment	Radionuclides	N	AM	ASD	GM	GSD	Min	Max
	IAEA	Mn	27	9.92E-01	1.68E+00	2.12E-01	7.55E+00	1.28E-02	7.73E+00
	SSAD	Mn	4	2.47E+00	1.61E+00	2.01E+00	2.20E+00	7.60E-01	4.11E+00
	IAEA	Ni	23	1.61E-01	1.71E-01	9.22E-02	3.04E+00	1.11E-02	5.66E-01
	SSAD	Ni	9	4.24E+00	6.31E+00	2.50E-01	2.23E+01	4.32E-03	1.40E+01
	IAEA	Pb	25	9.59E-03	1.30E-02	4.56E-03	3.53E+00	5.60E-04	5.24E-02
	SSAD	Pb	10	9.51E-02	7.04E-02	3.67E-02	1.29E+01	4.00E-05	2.05E-01
	IAEA	Rb	27	5.14E-02	1.12E-01	1.12E-02	5.11E+00	1.39E-03	4.74E-01
	SSAD	Rb	7	3.51E+00	3.15E+00	1.68E+00	4.86E+00	1.80E-01	7.33E+00
	IAEA	Sr	24	2.76E-02	4.87E-02	5.35E-03	6.36E+00	5.10E-04	1.78E-01
	SSAD	Sr	4	5.49E+00	1.85E+00	5.17E+00	1.54E+00	2.72E+00	6.48E+00
	IAEA	U	6	1.84E-03	2.77E-03	9.70E-04	3.02E+00	3.20E-04	7.46E-03
	SSAD	U	2	4.59E-03	3.47E-03	3.88E-03	2.32E+00	2.14E-03	7.04E-03
	IAEA	V	24	1.30E-02	1.90E-02	4.81E-03	4.65E+00	2.50E-04	6.59E-02
	SSAD	V	1	9.51E-05	.	9.51E-05	0.00E+00	1.00E-04	1.00E-04
	IAEA	Zn	27	7.39E-01	9.22E-01	3.67E-01	3.41E+00	6.64E-02	4.04E+00
	SSAD	Zn	21	5.61E-01	7.53E-01	8.79E-02	2.76E+01	1.00E-05	2.78E+00

Appendix 2. Concentration ratios for fresh water and marine wildlife (SSAD vs IAEA)

Wildlife	Environment	Elements	N	AM	ASD	GM	GSD	Min	Max
Crustacean	IAEA	Ba	2	7.31E+02	1.20E+02	7.26E+02	1.18E+00	6.46E+02	8.16E+02
	SSAD	Ba	16	7.30E+00	2.23E+01	7.29E-01	9.09E+00	2.60E-02	9.04E+01
	IAEA	Co	29	3.71E+03	4.15E+03	2.24E+03	3.04E+00	2.20E+02	2.20E+04
	SSAD	Co	2	1.75E+01	2.48E+01	1.18E-01	3.15E+03	0.00E+00	3.51E+01
Fish	IAEA	Ba	15	9.59E+00	7.15E+00	7.64E+00	2.00E+00	2.01E+00	2.89E+01
	SSAD	Ba	409	3.53E+02	1.14E+03	2.29E-01	7.58E+01	0.00E+00	6.25E+03
	IAEA	Co	93	5.72E+02	1.27E+03	2.16E+02	4.20E+00	3.18E+00	1.00E+04
	SSAD	Co	252	1.36E+02	6.39E+02	8.11E-02	3.71E+02	0.00E+00	7.64E+03
	IAEA	Mo	23	1.59E+00	4.40E-01	1.54E+00	1.31E+00	1.08E+00	2.43E+00
	SSAD	Mo	70	1.41E+01	2.09E+01	3.83E+00	1.10E+01	0.00E+00	9.18E+01
	IAEA	Rb	20	6.46E+01	3.05E+01	5.81E+01	1.61E+00	2.71E+01	1.29E+02
	SSAD	Rb	34	2.05E+02	1.76E+02	1.40E+02	2.57E+00	1.46E+01	6.74E+02
	IAEA	Se	41	1.01E+03	6.83E+02	8.50E+02	1.76E+00	3.71E+02	2.64E+03
	SSAD	Se	44	3.46E+01	3.34E+01	1.61E+01	4.33E+00	3.26E-01	1.09E+02
	IAEA	Sr	22	2.05E+01	2.82E+01	5.95E+00	6.99E+00	1.50E-01	9.37E+01
	SSAD	Sr	614	3.30E+02	9.37E+02	1.27E+01	3.08E+01	0.00E+00	7.97E+03
	IAEA	U	18	4.87E+00	6.23E+00	1.80E+00	4.69E+00	3.44E-01	1.83E+01
	SSAD	U	35	4.44E+00	3.58E+00	1.79E+00	7.74E+00	3.00E-03	1.18E+01
Macroalgae	IAEA	Ba	9	1.94E+03	1.15E+03	1.49E+03	2.40E+00	4.06E+02	3.33E+03
	SSAD	Ba	12	3.23E-01	2.15E-01	2.18E-01	3.29E+00	1.30E-02	8.08E-01
	IAEA	Co	135	5.10E+03	9.96E+03	1.28E+03	6.22E+00	9.78E+00	6.40E+04
	SSAD	Co	12	8.40E+00	8.63E+00	5.98E+00	2.29E+00	1.77E+00	3.36E+01
	IAEA	Mo	89	2.38E+01	3.41E+01	1.55E+01	2.50E+00	1.40E+00	3.08E+02
	SSAD	Mo	12	2.12E-01	2.80E-01	1.12E-01	3.17E+00	1.60E-02	9.69E-01
	IAEA	Sb	43	1.57E+02	2.35E+02	9.30E+01	2.64E+00	1.28E+01	1.50E+03
	SSAD	Sb	12	3.41E-02	5.37E-02	1.80E-02	2.88E+00	5.00E-03	1.98E-01

Appendix 3. Concentration ratios for food crops (SSAD vs IAEA)

Food Crop	Environment	Elements	N	AM	ASD	GM	GSD	Min	Max
Cereal	IAEA	Co	65	3.65E-02	4.12E-02	1.85E-02	3.88E+00	2.70E-04	1.87E-01
	SSAD	Co	16	6.98E-02	7.40E-02	1.47E-02	2.04E+01	1.00E-05	2.53E-01
Cereal	IAEA	Cr	1	2.00E-04	.	2.00E-04		2.00E-04	2.00E-04
	SSAD	Cr	160	3.40E-01	1.15E+00	8.16E-02	6.37E+00	1.00E-05	1.12E+01
Cereal	IAEA	Mn	108	1.85E+00	3.66E+00	6.05E-01	4.03E+00	5.36E-02	2.56E+01
	SSAD	Mn	64	3.98E-01	2.53E-01	2.83E-01	3.02E+00	2.83E-03	1.25E+00
Cereal	IAEA	Ni	44	3.52E-02	2.14E-02	2.81E-02	2.12E+00	3.35E-03	1.01E-01
	SSAD	Ni	59	6.11E-01	4.53E-01	4.41E-01	2.92E+00	1.26E-03	2.23E+00
Cereal	IAEA	Pb	13	2.10E-02	8.98E-03	1.88E-02	1.71E+00	5.56E-03	3.12E-02
	SSAD	Pb	502	2.77E-01	2.38E+00	3.45E-02	5.76E+00	2.00E-04	5.26E+01
Cereal	IAEA	Zn	114	3.76E+00	3.18E+00	2.75E+00	2.25E+00	3.42E-01	1.47E+01
	SSAD	Zn	212	9.50E-01	2.07E+00	3.08E-01	5.60E+00	5.00E-05	2.10E+01
Fruit	IAEA	Pb	5	1.09E-02	3.24E-03	1.05E-02	1.39E+00	6.64E-03	1.40E-02
	SSAD	Pb	56	2.32E+00	1.05E+01	1.56E-02	1.42E+01	2.40E-04	6.54E+01
Leafy Vegetable	IAEA	Ba	1	5.00E-03	.	5.00E-03		5.00E-03	5.00E-03
	SSAD	Ba	18	2.59E+00	3.61E+00	1.51E+00	2.78E+00	2.70E-01	1.60E+01
Leafy Vegetable	IAEA	Co	185	2.61E-01	2.02E-01	2.05E-01	2.01E+00	3.44E-02	1.33E+00
	SSAD	Co	625	1.81E+00	2.30E+00	4.55E-01	8.53E+00	1.88E-03	6.36E+00
Leafy Vegetable	IAEA	Cr	1	1.00E-03	.	1.00E-03		1.00E-03	1.00E-03
	SSAD	Cr	298	6.65E-01	2.72E+00	1.71E-01	4.78E+00	5.00E-04	3.55E+01
Leafy Vegetable	IAEA	Mn	103	5.76E-01	4.80E-01	4.35E-01	2.13E+00	8.00E-02	3.03E+00
	SSAD	Mn	746	6.03E-01	1.11E+00	1.78E-01	4.56E+00	1.58E-02	1.16E+01

Wildlife	Environment	Elements	N	AM	ASD	GM	GSD	Min	Max
Leafy Vegetable	IAEA	Mo	1	5.10E-01	.	5.10E-01		5.10E-01	5.10E-01
	SSAD	Mo	93	5.95E-01	5.17E-01	3.93E-01	2.67E+00	3.82E-02	2.43E+00
Leafy Vegetable	IAEA	Pb	31	2.38E+00	4.38E+00	6.60E-01	5.18E+00	3.41E-02	1.62E+01
	SSAD	Pb	901	2.46E+00	3.82E+00	3.57E-01	1.54E+01	0.00E+00	1.44E+01
Leafy Vegetable	IAEA	Rb	1	6.20E-01	.	6.20E-01		6.20E-01	6.20E-01
	SSAD	Rb	6	1.30E+01	3.78E+00	1.26E+01	1.30E+00	1.06E+01	2.04E+01
Leafy Vegetable	IAEA	Sr	217	1.98E+00	1.86E+00	1.40E+00	2.34E+00	1.25E-01	1.25E+01
	SSAD	Sr	17	1.79E+00	1.73E+00	1.31E+00	2.17E+00	3.00E-01	7.09E+00
Leafy Vegetable	IAEA	Zn	112	3.50E+00	2.64E+00	2.80E+00	1.96E+00	3.54E-01	1.84E+01
	SSAD	Zn	1103	2.08E+00	2.28E+00	1.06E+00	3.63E+00	2.08E-02	1.20E+01
Vegetable	IAEA	Ba	1	5.00E-03	.	5.00E-03		5.00E-03	5.00E-03
	SSAD	Ba	2	3.98E-02	7.95E-03	3.94E-02		3.42E-02	4.54E-02
Vegetable	IAEA	Co	7	1.56E-01	5.60E-02	1.49E-01	1.40E+00	1.10E-01	2.39E-01
	SSAD	Co	573	2.88E+00	1.20E+01	2.68E-01	6.99E+00	8.60E-04	1.12E+02
Vegetable	IAEA	Cr	1	1.00E-03	.	1.00E-03		1.00E-03	1.00E-03
	SSAD	Cr	244	4.21E+01	8.94E+01	6.97E-01	1.59E+01	3.00E-04	1.09E+03
Vegetable	IAEA	Mn	3	5.01E-01	1.56E-01	4.82E-01	1.42E+00	3.21E-01	6.05E-01
	SSAD	Mn	72	3.06E-01	5.31E-01	1.36E-01	3.52E+00	2.22E-02	4.00E+00
Vegetable	IAEA	Pb	7	2.71E-01	2.74E-01	1.01E-01	6.54E+00	8.28E-03	7.01E-01
	SSAD	Pb	972	5.16E+00	1.87E+01	6.34E-01	1.02E+01	7.10E-04	2.20E+02
Vegetable	IAEA	Sr	19	1.03E+00	1.90E+00	4.07E-01	3.80E+00	3.27E-02	7.99E+00
	SSAD	Sr	7	2.35E+00	1.96E+00	9.40E-01	8.08E+00	2.22E-02	5.66E+00

Food Crop	Environment	Stable Elements	N	AM	ASD	GM	GSD	Min	Max
Vegetable	IAEA	U	44	7.64E-02	2.36E-01	2.43E-02	4.00E+00	6.50E-04	1.58E+00
	SSAD	U	2	5.97E-01	8.27E-01	1.17E-01	2.63E+01	1.16E-02	1.18E+00
Vegetable	IAEA	Zn	89	1.34E+00	2.01E+00	6.75E-01	3.27E+00	4.60E-02	1.47E+01
	SSAD	Zn	1362	1.27E+00	1.75E+00	6.92E-01	3.56E+00	5.31E-03	3.53E+01
Legume	IAEA	Co	105	6.26E-02	8.86E-02	3.39E-02	3.07E+00	1.49E-03	5.65E-01
	SSAD	Co	27	6.67E-02	8.78E-02	3.03E-02	3.67E+00	4.20E-03	3.50E-01
Legume	IAEA	Mn	124	1.18E+00	2.17E+00	4.47E-01	3.78E+00	4.45E-02	1.56E+01
	SSAD	Mn	3	7.63E-01	3.23E-01	7.08E-01	1.65E+00	4.00E-01	1.02E+00
Legume	IAEA	Pb	18	1.42E-01	1.97E-01	5.32E-02	5.74E+00	8.80E-04	7.13E-01
	SSAD	Pb	56	4.20E-02	1.24E-01	1.54E-02	2.77E+00	1.09E-02	8.69E-01
Legume	IAEA	Sr	148	2.00E+00	1.32E+00	1.63E+00	1.95E+00	2.32E-01	7.58E+00
	SSAD	Sr	3	3.59E+00	5.37E-01	3.56E+00	1.16E+00	3.20E+00	4.20E+00
Maize	IAEA	Co	77	4.06E-02	4.06E-02	2.35E-02	3.43E+00	6.00E-04	2.27E-01
	SSAD	Co	47	7.71E-01	3.09E+00	1.43E-02	3.24E+01	4.00E-05	2.08E+01
Maize	IAEA	Mn	19	1.06E-01	5.83E-02	9.24E-02	1.75E+00	2.50E-02	2.72E-01
	SSAD	Mn	11	4.67E-01	3.77E-01	2.79E-01	3.52E+00	3.00E-02	1.00E+00
Maize	IAEA	Mo	3	7.30E-01	0.00E+00	7.30E-01	1.00E+00	7.30E-01	7.30E-01
	SSAD	Mo	7	2.83E+00	3.37E+00	1.89E+00	2.45E+00	6.30E-01	1.03E+01
Maize	IAEA	Pb	12	3.82E-03	3.13E-03	2.51E-03	2.80E+00	5.80E-04	8.70E-03
	SSAD	Pb	115	1.61E+00	1.63E+01	2.52E-02	6.21E+00	3.40E-04	1.75E+02
Maize	IAEA	Sr	75	7.70E-01	6.00E-01	5.79E-01	2.20E+00	6.86E-02	2.54E+00
	SSAD	Sr	2	8.55E-01	7.78E-02	8.53E-01	1.10E+00	8.00E-01	9.10E-01
Maize	IAEA	Zn	19	1.26E+00	1.97E+00	7.51E-01	2.30E+00	2.63E-01	7.48E+00
	SSAD	Zn	38	1.28E+00	2.79E+00	2.33E-01	7.53E+00	1.13E-02	1.56E+01
Root	IAEA	Co	16	1.54E-01	1.34E-01	1.02E-01	2.83E+00	1.46E-02	5.25E-01
	SSAD	Co	138	3.30E-01	5.86E-01	9.75E-02	5.89E+00	4.70E-04	5.03E+00
Root	IAEA	Cr	1	1.00E-03	.	1.00E-03		1.00E-03	1.00E-03

Wildlife	Environ	Stable Elements	N	AM	ASD	GM	GSD	Min	Max
	SSAD	Cr	145	3.82E-01	1.11E+00	1.77E-01	3.35E+00	4.35E-03	1.32E+01
Root	IAEA	Cs	93	7.41E-02	1.43E-01	4.19E-02	2.62E+00	4.52E-03	1.29E+00
	SSAD	Cs	7	3.07E-01	1.96E-01	2.41E-01	2.26E+00	6.26E-02	5.17E-01
Root	IAEA	Mn	13	1.48E+00	1.52E+00	1.04E+00	2.34E+00	2.87E-01	5.98E+00
	SSAD	Mn	107	2.17E-01	3.49E-01	9.11E-02	3.86E+00	5.00E-03	1.80E+00
Root	IAEA	Pb	27	5.85E-01	7.40E-01	2.89E-01	3.43E+00	3.89E-02	2.79E+00
	SSAD	Pb	294	1.39E+00	4.86E+00	1.47E-01	1.59E+01	5.00E-05	6.24E+01
Root	IAEA	Rb	1	9.00E-01	.	9.00E-01		9.00E-01	9.00E-01
	SSAD	Rb	8	3.28E+00	2.21E+00	2.72E+00	1.97E+00	7.42E-01	8.20E+00
Root	IAEA	Sb	5	5.01E-04	1.69E-04	4.76E-04	1.44E+00	2.80E-04	7.10E-04
	SSAD	Sb	8	3.49E-01	2.12E-01	3.10E-01	1.63E+00	1.76E-01	8.35E-01
Root	IAEA	Sr	56	1.26E+00	1.15E+00	9.74E-01	2.00E+00	2.46E-01	7.07E+00
	SSAD	Sr	1	5.70E+00	.	5.70E+00		5.70E+00	5.70E+00
Root	IAEA	U	83	5.86E-02	9.37E-02	2.77E-02	3.50E+00	1.59E-03	6.78E-01
	SSAD	U	6	2.01E-02	2.15E-02	1.34E-02	2.54E+00	5.99E-03	5.99E-02
Root	IAEA	Zn	3	7.61E+00	6.26E+00	3.97E+00	5.94E+00	5.10E-01	1.23E+01
	SSAD	Zn	277	8.24E+00	4.59E+01	5.50E-01	6.96E+00	3.21E-03	3.90E+02
Tuber	IAEA	Ba	1	5.00E-03	.	5.00E-03		5.00E-03	5.00E-03
	SSAD	Ba	3	4.33E-01	2.10E-01	3.96E-01	1.72E+00	2.20E-01	6.40E-01
Tuber	IAEA	Co	56	7.46E-02	7.27E-02	5.11E-02	2.44E+00	7.52E-03	3.53E-01
	SSAD	Co	203	1.25E-01	1.75E-01	2.95E-02	7.00E+00	9.30E-04	6.19E-01
Tuber	IAEA	Cr	1	5.00E-04	.	5.00E-04		5.00E-04	5.00E-04
	SSAD	Cr	150	7.93E-02	1.51E-01	4.30E-02	2.45E+00	1.07E-02	9.67E-01
Tuber	IAEA	Cs	138	9.46E-02	9.82E-02	6.13E-02	2.658721	4.07E-03	5.91E-01
	SSAD	Cs	4	2.33E-02	1.12E-02	2.11E-02	1.703658	1.08E-02	3.60E-02
Tuber	IAEA	Mn	23	6.87E-02	1.01E-01	4.46E-02	2.30E+00	1.06E-02	5.11E-01
	SSAD	Mn	184	1.86E-01	2.99E-01	5.07E-02	6.01E+00	1.73E-03	1.18E+00
Tuber	IAEA	Pb	30	1.52E-01	2.60E-01	2.91E-02	7.69E+00	1.03E-03	8.68E-01

Wildlife	Environ	Stable Elements	N	AM	ASD	GM	GSD	Min	Max
Tuber	IAEA	Sb	1	2.00E-03	.	2.00E-03		2.00E-03	2.00E-03
	SSAD	Sb	16	3.73E-01	2.29E-01	3.26E-01	1.66E+00	1.66E-01	1.04E+00
Tuber	IAEA	Sr	106	2.47E-01	1.71E-01	1.96E-01	2.044635	2.35E-02	8.36E-01
	SSAD	Sr	4	1.58E+00	9.18E-01	1.33E+00	2.067867	5.00E-01	2.60E+00
Tuber	IAEA	U	29	2.51E-02	3.85E-02	1.34E-02	2.93E+00	1.36E-03	1.90E-01
	SSAD	U	4	1.46E-02	7.96E-03	1.30E-02	1.76E+00	6.37E-03	2.55E-02
Tuber	IAEA	Zn	20	3.41E-01	1.60E-01	3.11E-01	1.53E+00	1.60E-01	7.50E-01
	SSAD	Zn	185	8.71E-01	1.57E+00	2.27E-01	5.58E+00	9.95E-03	8.17E+00

Appendix 4. Concentration in biota (wildlife)

Wildlife	Location	Elements	N	AM	ASD	GM	GSD	Min	Max
Bee	Geregu	Cs	5	2.15E-02	8.66E-03	2.03E-02	1.43E+00	1.34E-02	3.63E-02
	Itu		5	3.36E-02	1.48E-02	3.06E-02	1.66E+00	1.60E-02	4.93E-02
	Geregu	Se	5	9.90E-03	1.88E-03	9.76E-03	1.20E+00	8.05E-03	1.28E-02
	Itu		5	1.69E-01	4.35E-02	1.65E-01	1.28E+00	1.25E-01	2.35E-01
	Geregu	Sr	5	6.35E+00	2.35E+00	5.99E+00	1.47E+00	3.71E+00	8.77E+00
	Itu		5	1.34E+00	1.49E-01	1.33E+00	1.12E+00	1.15E+00	1.51E+00
	Geregu	Co	5	4.43E-03	3.79E-03	3.60E-03	1.92E+00	2.06E-03	1.12E-02
	Itu		5	2.27E-02	3.39E-03	2.24E-02	1.17E+00	1.75E-02	2.69E-02
	Geregu	U	5	1.41E-04	3.36E-05	1.38E-04	1.31E+00	9.00E-05	1.70E-04
	Itu		5	1.61E-04	3.35E-05	1.59E-04	1.22E+00	1.30E-04	2.10E-04
	Geregu	Th	5	3.42E-04	1.45E-04	3.20E-04	1.49E+00	1.90E-04	5.80E-04
	Itu		5	3.12E-04	0.00E+00	3.12E-04	1.00E+00	3.10E-04	3.10E-04
	Geregu	Ce	5	3.01E-02	5.90E-03	2.96E-02	1.22E+00	2.38E-02	3.75E-02
	Itu		5	3.90E-02	4.24E-03	3.88E-02	1.11E+00	3.38E-02	4.48E-02
	Geregu	Eu	5	5.05E-05	1.52E-05	4.87E-05	1.36E+00	3.00E-05	7.00E-05

Wildlife	Location	Elements	N	AM	ASD	GM	GSD	Min	Max
	Itu		5	4.00E-05	7.27E-06	3.95E-05	1.20E+00	3.00E-05	5.00E-05
	Geregu	Mo	5	5.27E-03	5.17E-03	3.48E-03	2.87E+00	1.05E-03	1.38E-02
	Itu		5	1.23E-02	1.85E-03	1.22E-02	1.16E+00	1.04E-02	1.47E-02
Earthworm	Geregu	Cs	5	2.08E-02	6.83E-03	1.99E-02	1.37E+00	1.33E-02	3.18E-02
	Itu		4	1.93E-02	1.77E-03	1.92E-02	1.10E+00	1.66E-02	2.02E-02
	Geregu	Se	5	4.32E-02	2.59E-02	3.66E-02	1.95E+00	1.49E-02	7.51E-02
	Itu		2	1.60E-02	1.07E-03	1.60E-02	1.07E+00	1.53E-02	1.68E-02
	Geregu	Sr	5	2.56E+00	9.57E-01	2.41E+00	1.50E+00	1.46E+00	3.57E+00
	Itu		2	4.53E-01	4.03E-02	4.52E-01	1.09E+00	4.25E-01	4.82E-01
	Geregu	Co	5	4.74E-03	5.39E-03	3.35E-03	2.26E+00	2.33E-03	1.44E-02
	Itu		2	6.03E-03	8.02E-04	6.00E-03	1.14E+00	5.46E-03	6.59E-03
	Geregu	U	5	2.47E-03	5.59E-04	2.42E-03	1.25E+00	1.88E-03	3.14E-03
	Itu		2	7.83E-04	1.28E-04	7.78E-04	1.18E+00	6.90E-04	8.70E-04
	Geregu	Th	5	2.06E-02	5.97E-03	1.99E-02	1.34E+00	1.48E-02	2.84E-02
	Itu		2	3.78E-03	1.14E-03	3.69E-03	1.36E+00	2.97E-03	4.58E-03
	Geregu	Ce	5	5.14E-02	9.22E-03	5.07E-02	1.21E+00	3.78E-02	6.08E-02
	Itu		2	2.33E-02	3.53E-03	2.32E-02	1.16E+00	2.08E-02	2.58E-02
	Geregu	Eu	5	3.95E-04	8.34E-05	3.88E-04	1.23E+00	3.00E-04	5.10E-04
	Itu		2	9.57E-05	7.73E-06	9.56E-05	1.08E+00	9.00E-05	1.00E-04
	Geregu	Mo	5	4.27E-03	2.31E-03	3.43E-03	2.41E+00	7.50E-04	7.04E-03
	Itu		4	1.42E-02	1.69E-02	0.00E+00	1.28E+00	0.00E+00	3.32E-02
Frog	Geregu	Cs	9	4.18E-02	1.24E-02	4.03E-02	1.34E+00	2.69E-02	6.39E-02
	Itu		9	6.24E-02	1.66E-02	6.07E-02	1.28E+00	4.45E-02	9.79E-02
	Geregu	Se	9	7.12E-03	2.38E-03	6.77E-03	1.41E+00	3.51E-03	1.15E-02
	Itu		9	1.82E-02	9.06E-03	1.68E-02	1.47E+00	1.20E-02	4.07E-02
	Geregu	Sr	9	1.67E+01	7.88E+00	1.51E+01	1.64E+00	5.80E+00	3.30E+01
	Itu		9	1.33E+01	4.32E+00	1.28E+01	1.34E+00	9.13E+00	2.32E+01
	Geregu	Co	9	9.85E-03	4.20E-03	9.01E-03	1.60E+00	3.36E-03	1.85E-02
	Itu		9	1.38E-02	2.36E-03	1.36E-02	1.20E+00	9.10E-03	1.78E-02

Wildlife	Location	Elements	N	AM	ASD	GM	GSD	Min	Max
	Geregu	U	9	6.12E-05	1.98E-05	5.82E-05	1.42E+00	3.00E-05	1.00E-04
	Itu		9	1.02E-04	8.07E-05	7.35E-05	2.71E+00	1.00E-05	2.90E-04
	Geregu	Th	9	3.33E-04	0.00E+00	3.33E-04	1.00E+00	3.30E-04	3.30E-04
	Itu		9	4.69E-04	4.08E-04	3.96E-04	1.67E+00	3.30E-04	1.56E-03
	Geregu	Ce	9	3.13E-02	6.73E-03	3.07E-02	1.24E+00	2.19E-02	4.27E-02
	Itu		9	3.25E-02	6.27E-03	3.20E-02	1.19E+00	2.60E-02	4.64E-02
	Geregu	Eu	9	3.01E-05	1.33E-05	2.72E-05	1.66E+00	1.00E-05	5.00E-05
	Itu		9	1.32E-05	7.99E-06	1.04E-05	2.34E+00	0.00E+00	3.00E-05
	Geregu	Mo	9	1.48E-02	1.76E-02	6.07E-03	5.00E+00	3.40E-04	4.46E-02
	Itu		9	1.48E-02	1.13E-03	1.48E-02	1.08E+00	1.33E-02	1.63E-02
Grass	Geregu	Cs	5	1.83E-02	3.94E-03	1.79E-02	1.26E+00	1.25E-02	2.18E-02
	Itu		5	4.41E-02	1.97E-02	4.10E-02	1.51E+00	2.74E-02	7.53E-02
	Geregu	Se	5	4.93E-03	2.84E-03	4.25E-03	1.87E+00	1.84E-03	8.69E-03
	Itu		5	3.87E-02	6.65E-02	1.58E-02	3.62E+00	8.48E-03	1.58E-01
	Geregu	Sr	5	2.22E+00	3.08E-01	2.21E+00	1.14E+00	1.94E+00	2.73E+00
	Itu		5	2.06E+00	3.75E-01	2.03E+00	1.19E+00	1.73E+00	2.63E+00
	Geregu	Co	5	1.43E-02	5.04E-03	1.35E-02	1.51E+00	7.08E-03	1.86E-02
	Itu		5	1.98E-02	3.51E-03	1.95E-02	1.20E+00	1.59E-02	2.39E-02
	Geregu	U	5	1.48E-04	1.94E-05	1.47E-04	1.14E+00	1.20E-04	1.70E-04
	Itu		5	6.07E-05	1.01E-05	6.01E-05	1.18E+00	5.00E-05	7.00E-05
	Geregu	Th	5	3.61E-04	2.79E-05	3.60E-04	1.08E+00	3.10E-04	3.70E-04
	Itu		5	3.74E-04	0.00E+00	3.74E-04	1.00E+00	3.70E-04	3.70E-04
	Geregu	Ce	5	2.80E-02	1.93E-03	2.79E-02	1.07E+00	2.47E-02	2.96E-02
	Itu		5	3.14E-02	3.93E-03	3.12E-02	1.13E+00	2.62E-02	3.70E-02
	Geregu	Eu	5	3.84E-05	9.51E-06	3.74E-05	1.30E+00	3.00E-05	5.00E-05
	Itu		5	2.08E-05	6.36E-06	1.99E-05	1.43E+00	1.00E-05	3.00E-05
	Geregu	Mo	5	7.96E-03	5.25E-03	6.60E-03	2.05E+00	2.22E-03	1.65E-02
	Itu		5	1.62E-02	2.06E-03	1.61E-02	1.14E+00	1.36E-02	1.84E-02
Rat	Geregu	Cs	1	5.79E-02	.	5.79E-02		5.79E-02	5.79E-02

Wildlife	Location	Elements	N	AM	ASD	GM	GSD	Min	Max
	Itu		4	7.32E-02	1.99E-02	7.11E-02	1.33E+00	4.92E-02	9.78E-02
	Geregu	Se	1	7.72E-03	.	7.72E-03		7.72E-03	7.72E-03
	Itu		4	2.21E-02	2.44E-03	2.20E-02	1.11E+00	1.99E-02	2.55E-02
	Geregu	Sr	1	6.76E+00	.	6.76E+00		6.76E+00	6.76E+00
	Itu		4	3.76E+00	3.76E-01	3.75E+00	1.11E+00	3.21E+00	4.03E+00
	Geregu	Co	1	1.84E-02	.	1.84E-02		1.84E-02	1.84E-02
	Itu		4	1.87E-02	2.40E-03	1.86E-02	1.14E+00	1.53E-02	2.07E-02
	Geregu	U	1	1.42E-04	.	1.42E-04		1.40E-04	1.40E-04
	Itu		4	1.94E-04	1.24E-04	1.11E-04	5.32E+00	1.00E-05	2.70E-04
	Geregu	Th	1	3.96E-04	.	3.96E-04		4.00E-04	4.00E-04
	Itu		4	6.86E-04	5.81E-04	5.57E-04	1.98E+00	4.00E-04	1.56E-03
	Geregu	Ce	1	3.80E-02	.	3.80E-02		3.80E-02	3.80E-02
	Itu		4	4.39E-02	4.56E-03	4.37E-02	1.11E+00	3.75E-02	4.82E-02
	Geregu	Eu	1	1.89E-05	.	1.89E-05		2.00E-05	2.00E-05
	Itu		4	4.24E-05	7.32E-06	4.19E-05	1.19E+00	4.00E-05	5.00E-05
	Geregu	Mo	1	1.53E-03	.	1.53E-03		1.53E-03	1.53E-03
	Itu		4	2.00E-02	3.77E-03	1.98E-02	1.19E+00	1.72E-02	2.56E-02

Appendix 5. Concentration in soil (wildlife)

Wildlife	Location	Elements	N	AM	ASD	GM	GSD	Min	Max
Bee	Geregu	Cs	5	1.15E+00	2.01E-01	1.14E+00	1.18E+00	9.76E-01	1.44E+00
	Itu	Cs	5	4.47E-01	3.96E-02	4.45E-01	1.09E+00	4.06E-01	5.08E-01
	Geregu	Se	5	4.13E-01	1.74E-01	3.73E-01	1.74E+00	1.45E-01	6.16E-01
	Itu	Se	5	1.21E-01	3.12E-02	1.17E-01	1.29E+00	9.20E-02	1.65E-01
	Geregu	Sr	5	5.77E+00	2.38E+00	5.34E+00	1.58E+00	2.69E+00	8.70E+00
	Itu	Sr	5	4.41E+00	2.73E+00	1.56E+00	1.60E+01	1.11E-02	7.48E+00

	Geregu	Co	5	1.59E-01	8.64E-02	1.22E-01	2.72E+00	2.12E-02	2.37E-01
Wildlife	**Location**	**Elements**	**N**	**AM**	**ASD**	**GM**	**GSD**	**Min**	**Max**
	Itu	Co	5	4.54E-02	6.37E-02	1.92E-02	4.62E+00	3.58E-03	1.56E-01
	Geregu	U	5	1.58E-02	5.27E-03	1.47E-02	1.59E+00	6.48E-03	1.93E-02
	Itu	U	5	1.08E-02	8.56E-03	5.64E-03	4.97E+00	5.10E-04	1.70E-02
	Geregu	Th	5	1.79E-01	7.13E-02	1.59E-01	1.86E+00	5.27E-02	2.25E-01
	Itu	Th	5	1.56E-03	0.00E+00	1.56E-03	1.00E+00	1.56E-03	1.56E-03
	Geregu	Ce	5	1.20E+00	7.58E-01	9.34E-01	2.43E+00	2.44E-01	2.01E+00
	Itu	Ce	5	1.40E-01	2.57E-01	2.29E-02	9.19E+00	4.87E-03	5.94E-01
	Geregu	Eu	5	3.96E-03	1.24E-03	3.79E-03	1.41E+00	2.20E-03	5.62E-03
	Itu	Eu	5	1.22E-03	6.32E-04	8.61E-04	3.49E+00	9.00E-05	1.51E-03
	Geregu	Mo	5	1.94E-01	7.41E-02	1.78E-01	1.67E+00	7.41E-02	2.63E-01
	Itu	Mo	5	6.06E-02	6.04E-02	3.12E-02	4.91E+00	2.41E-03	1.54E-01
Earthworm	Geregu	Cs	5	1.33E+00	4.76E-01	1.27E+00	1.36E+00	1.03E+00	2.17E+00
	Itu	Cs	4	4.60E-01	6.10E-02	4.57E-01	1.15E+00	3.75E-01	5.21E-01
	Geregu	Se	5	1.17E+00	5.88E-01	9.84E-01	2.16E+00	2.62E-01	1.85E+00
	Itu	Se	2	1.82E-01	8.13E-02	1.72E-01	1.59E+00	1.24E-01	2.39E-01
	Geregu	Sr	5	5.84E+01	4.22E+01	3.68E+01	4.04E+00	3.29E+00	1.21E+02
	Itu	Sr	2	1.21E+02	0.00E+00	1.21E+02	1.00E+00	1.21E+02	1.21E+02
	Geregu	Co	5	1.65E-01	9.75E-02	1.43E-01	1.84E+00	5.82E-02	3.25E-01
	Itu	Co	2	2.19E-02	2.51E-02	1.28E-02	4.95E+00	4.14E-03	3.97E-02
	Geregu	U	5	1.28E-02	3.06E-03	1.26E-02	1.25E+00	9.90E-03	1.76E-02
	Itu	U	2	1.13E-02	0.00E+00	1.13E-02	1.00E+00	1.13E-02	1.13E-02
	Geregu	Th	5	1.10E-01	7.45E-02	5.36E-02	7.42E+00	1.56E-03	1.91E-01
	Itu	Th	2	1.56E-03	0.00E+00	1.56E-03	1.00E+00	1.56E-03	1.56E-03
	Geregu	Ce	5	6.46E-01	5.83E-01	2.60E-01	9.77E+00	4.87E-03	1.58E+00
	Itu	Ce	2	4.09E-01	0.00E+00	4.09E-01	1.00E+00	4.09E-01	4.09E-01
	Geregu	Eu	5	2.31E-03	8.99E-04	2.11E-03	1.70E+00	8.40E-04	3.30E-03
	Itu	Eu	2	1.51E-03	0.00E+00	1.51E-03	1.00E+00	1.51E-03	1.51E-03
	Geregu	Mo	5	1.91E-01	7.71E-02	1.73E-01	1.77E+00	6.44E-02	2.52E-01
	Itu	Mo	2	1.10E-01	5.59E-02	1.03E-01	1.70E+00	7.04E-02	1.50E-01

Frog	Geregu	Cs	9	8.27E-01	2.33E-01	7.98E-01	1.33E+00	5.03E-01	1.28E+00
Wildlife	**Location**	**Elements**	**N**	**AM**	**ASD**	**GM**	**GSD**	**Min**	**Max**
	Itu		9	7.14E-01	2.65E-01	6.67E-01	1.49E+00	3.75E-01	1.10E+00
	Geregu	Se	9	2.80E-01	1.78E-01	1.93E-01	3.46E+00	8.70E-03	6.33E-01
	Itu		9	2.35E-01	2.07E-01	1.54E-01	2.79E+00	3.83E-02	5.59E-01
	Geregu	Sr	9	3.74E+00	5.08E-01	3.70E+00	1.17E+00	2.46E+00	3.99E+00
	Itu		9	4.06E+00	2.10E-01	4.06E+00	1.05E+00	3.99E+00	4.62E+00
	Geregu	Co	9	2.54E-01	1.43E-01	2.03E-01	2.29E+00	3.20E-02	4.55E-01
	Itu		9	4.43E-02	2.27E-02	3.58E-02	2.37E+00	4.14E-03	8.44E-02
	Geregu	U	9	5.36E-03	5.54E-03	3.20E-03	2.92E+00	9.10E-04	1.38E-02
	Itu		9	1.09E-02	1.40E-02	3.09E-03	9.47E+00	4.00E-05	3.86E-02
	Geregu	Th	9	7.57E-02	5.53E-02	5.96E-02	2.10E+00	2.23E-02	1.81E-01
	Itu		9	6.91E-02	1.43E-01	1.26E-02	8.36E+00	1.56E-03	4.46E-01
	Geregu	Ce	9	3.73E-01	4.49E-01	6.24E-02	1.28E+01	4.87E-03	1.11E+00
	Itu		9	8.58E-01	1.49E+00	2.03E-01	8.63E+00	4.87E-03	4.73E+00
	Geregu	Eu	9	1.44E-03	8.34E-04	1.19E-03	2.06E+00	2.90E-04	2.72E-03
	Itu		9	1.62E-03	2.39E-03	7.96E-04	3.71E+00	1.10E-04	7.86E-03
	Geregu	Mo	9	1.23E-01	6.55E-02	1.06E-01	1.84E+00	4.85E-02	2.21E-01
	Itu		9	7.36E-02	4.98E-02	5.99E-02	2.00E+00	1.85E-02	1.59E-01
Grass	Geregu	Cs	5	1.09E+00	2.22E-01	1.07E+00	1.24E+00	7.79E-01	1.39E+00
	Itu		5	5.23E-01	1.51E-01	5.08E-01	1.29E+00	4.06E-01	7.83E-01
	Geregu	Se	5	7.72E-01	7.82E-01	4.35E-01	3.71E+00	7.36E-02	1.85E+00
	Itu		5	2.73E-01	2.08E-01	1.95E-01	2.78E+00	4.23E-02	5.59E-01
	Geregu	Sr	5	2.43E+01	3.03E+01	8.19E+00	6.40E+00	8.76E-01	6.61E+01
	Itu		5	5.31E+01	2.92E+01	2.78E+01	6.94E+00	8.68E-01	6.61E+01
	Geregu	Co	5	1.01E-01	7.77E-02	7.96E-02	2.18E+00	3.17E-02	2.18E-01
	Itu		5	3.90E-02	2.40E-02	2.84E-02	3.03E+00	4.14E-03	7.20E-02
	Geregu	U	5	1.47E-02	7.37E-03	1.27E-02	1.92E+00	4.45E-03	2.19E-02
	Itu		5	3.98E-03	3.31E-03	2.24E-03	4.14E+00	3.40E-04	7.92E-03
	Geregu	Th	5	1.64E-01	9.80E-02	1.33E-01	2.22E+00	3.95E-02	2.64E-01
	Itu		5	1.60E-02	2.01E-02	5.55E-03	5.72E+00	1.56E-03	4.28E-02

	Geregu	Ce	5	7.53E-01	7.72E-01	4.96E-01	2.88E+00	1.14E-01	2.08E+00
Wildlife	**Location**	**Elements**	**N**	**AM**	**ASD**	**GM**	**GSD**	**Min**	**Max**
	Itu		5	4.05E-01	3.30E-01	2.35E-01	4.03E+00	3.21E-02	8.01E-01
	Geregu	Eu	5	4.24E-03	3.93E-03	2.99E-03	2.64E+00	7.70E-04	1.08E-02
	Itu		5	6.89E-04	6.01E-04	4.24E-04	3.43E+00	1.10E-04	1.51E-03
	Geregu	Mo	5	1.66E-01	9.66E-02	1.38E-01	2.09E+00	5.37E-02	2.52E-01
	Itu		5	9.04E-02	6.19E-02	6.99E-02	2.41E+00	1.85E-02	1.59E-01
Rat	Geregu	Cs	1	8.48E-01	.	8.48E-01		8.48E-01	8.48E-01
	Itu		4	4.75E-01	4.60E-02	4.73E-01	1.10E+00	4.29E-01	5.21E-01
	Geregu	Se	1	3.70E-01	.	3.70E-01		3.70E-01	3.70E-01
	Itu		4	1.08E-01	4.66E-02	1.00E-01	1.61E+00	5.36E-02	1.63E-01
	Geregu	Sr	1	3.59E+00	.	3.59E+00		3.59E+00	3.59E+00
	Itu		4	3.59E+00	0.00E+00	3.59E+00	1.00E+00	3.59E+00	3.59E+00
	Geregu	Co	1	4.55E-01	.	4.55E-01		4.55E-01	4.55E-01
	Itu		4	7.13E-02	5.84E-02	4.26E-02	4.18E+00	5.79E-03	1.30E-01
	Geregu	U	1	1.38E-02	.	1.38E-02		1.38E-02	1.38E-02
	Itu		4	6.94E-03	7.93E-03	9.88E-04	2.11E+01	6.00E-05	1.38E-02
	Geregu	Th	1	1.81E-01	.	1.81E-01		1.81E-01	1.81E-01
	Itu		4	5.06E-03	7.01E-03	2.77E-03	3.16E+00	1.56E-03	1.56E-02
	Geregu	Ce	1	6.16E-01	.	6.16E-01		6.16E-01	6.16E-01
	Itu		4	3.11E-01	3.53E-01	5.48E-02	1.64E+01	4.87E-03	6.16E-01
	Geregu	Eu	1	2.31E-03	.	2.31E-03		2.31E-03	2.31E-03
	Itu		4	1.51E-03	0.00E+00	1.51E-03	1.00E+00	1.51E-03	1.51E-03
	Geregu	Mo	1	6.20E-02	.	6.20E-02		6.20E-02	6.20E-02
	Itu		4	6.72E-02	5.64E-02	5.33E-02	2.12E+00	3.05E-02	1.50E-01

Appendix 6. Concentration ratios for wildlife (Geregu vs Itu)

Wildlife	Location	Elements	N	AM	ASD	Min	Max	GM	GSD
Bee	Geregu	Cs	5	1.85E-02	5.30E-03	1.05E-02	2.52E-02	1.78E-02	1.38E+00
	Itu	Cs	5	7.43E-02	2.97E-02	3.58E-02	9.72E-02	6.87E-02	1.60E+00
	Geregu	Se	5	3.03E-02	1.93E-02	1.43E-02	6.24E-02	2.62E-02	1.80E+00
	Itu	Se	5	1.44E+00	3.54E-01	1.10E+00	2.02E+00	1.41E+00	1.26E+00
	Geregu	Sr	5	1.24E+00	5.00E-01	4.26E-01	1.66E+00	1.12E+00	1.75E+00
	Itu	Sr	5	2.08E+01	4.60E+01	1.65E-01	1.03E+02	8.53E-01	1.48E+01
	Geregu	Co	5	1.17E-01	2.28E-01	9.10E-03	5.26E-01	2.94E-02	5.18E+00
	Itu	Co	5	1.99E+00	2.51E+00	1.12E-01	6.32E+00	9.58E-01	4.45E+00
	Geregu	U	5	1.09E-02	7.26E-03	4.58E-03	2.33E-02	9.34E-03	1.81E+00
	Itu	U	5	8.89E-02	1.52E-01	7.99E-03	3.59E-01	2.81E-02	5.07E+00
	Geregu	Th	5	2.53E-03	2.03E-03	8.90E-04	5.91E-03	2.01E-03	2.09E+00
	Itu	Th	5	2.00E-01	0.00E+00	2.00E-01	2.00E-01	2.00E-01	1.00E+00
	Geregu	Ce	5	4.35E-02	3.88E-02	1.47E-02	1.03E-01	3.17E-02	2.40E+00
	Itu	Ce	5	4.76E+00	4.13E+00	6.24E-02	8.51E+00	1.70E+00	9.01E+00
	Geregu	Eu	5	1.41E-02	6.88E-03	8.45E-03	2.32E-02	1.29E-02	1.61E+00
	Itu	Eu	5	1.25E-01	2.23E-01	2.08E-02	5.23E-01	4.59E-02	3.93E+00
	Geregu	Mo	5	3.33E-02	3.43E-02	5.71E-03	8.23E-02	1.96E-02	3.33E+00
	Itu	Mo	5	1.42E+00	2.61E+00	7.62E-02	6.08E+00	3.90E-01	5.49E+00
Earthworm	Geregu	Cs	5	1.73E-02	8.34E-03	8.36E-03	2.92E-02	1.56E-02	1.66E+00
	Itu		4	4.25E-02	8.19E-03	3.52E-02	5.39E-02	4.20E-02	1.20E+00
	Geregu	Se	5	7.51E-02	1.01E-01	8.07E-03	2.49E-01	3.72E-02	3.76E+00
	Itu		2	9.93E-02	5.03E-02	6.37E-02	1.35E-01	9.27E-02	1.70E+00
	Geregu	Sr	5	2.31E-01	4.41E-01	2.54E-02	1.02E+00	6.53E-02	4.75E+00
	Itu		2	3.76E-03	3.34E-04	3.52E-03	3.99E-03	3.75E-03	1.09E+00
	Geregu	Co	5	3.49E-02	3.58E-02	7.17E-03	9.50E-02	2.34E-02	2.70E+00
	Itu		2	8.66E-01	1.03E+00	1.38E-01	1.59E+00	4.68E-01	5.65E+00

	Geregu	U	5	2.06E-01	8.49E-02	1.15E-01	3.17E-01	1.92E-01	1.54E+00
Wildlife	**Location**	**Elements**	**N**	**AM**	**ASD**	**GM**	**GSD**	**Min**	**Max**
	Itu		2	6.91E-02	1.13E-02	6.11E-02	7.71E-02	6.86E-02	1.18E+00
	Geregu	Th	5	2.65E+00	5.51E+00	7.71E-02	1.25E+01	3.71E-01	7.83E+00
	Itu		2	2.42E+00	7.33E-01	1.91E+00	2.94E+00	2.37E+00	1.36E+00
	Geregu	Ce	5	2.04E+00	4.36E+00	3.26E-02	9.84E+00	1.95E-01	9.67E+00
	Itu		2	5.70E-02	8.63E-03	5.09E-02	6.31E-02	5.66E-02	1.16E+00
	Geregu	Eu	5	2.13E-01	1.41E-01	1.04E-01	4.53E-01	1.84E-01	1.79E+00
	Itu		2	6.36E-02	5.13E-03	6.00E-02	6.72E-02	6.35E-02	1.08E+00
	Geregu	Mo	5	3.00E-02	2.79E-02	3.59E-03	7.66E-02	1.99E-02	3.08E+00
	Itu		2	2.78E-01	7.92E-02	2.22E-01	3.34E-01	2.72E-01	1.33E+00
Frog	Geregu	Cs	9	5.36E-02	1.75E-02	2.19E-02	7.35E-02	5.04E-02	1.48E+00
	Itu		9	1.06E-01	6.93E-02	5.21E-02	2.61E-01	9.10E-02	1.77E+00
	Geregu	Se	9	9.93E-02	2.09E-01	5.54E-03	6.55E-01	3.51E-02	3.71E+00
	Itu		9	1.45E-01	1.13E-01	3.37E-02	3.39E-01	1.09E-01	2.28E+00
	Geregu	Sr	9	4.47E+00	1.95E+00	1.60E+00	8.25E+00	4.07E+00	1.61E+00
	Itu		9	3.28E+00	1.10E+00	2.29E+00	5.81E+00	3.15E+00	1.34E+00
	Geregu	Co	9	5.90E-02	6.65E-02	2.42E-02	2.35E-01	4.43E-02	1.96E+00
	Itu		9	5.28E-01	6.33E-01	1.75E-01	2.20E+00	3.80E-01	2.07E+00
	Geregu	U	9	2.92E-02	2.53E-02	2.29E-03	8.33E-02	1.82E-02	3.27E+00
	Itu		9	9.65E-02	1.44E-01	2.61E-03	4.03E-01	2.38E-02	6.43E+00
	Geregu	Th	9	7.01E-03	4.76E-03	1.84E-03	1.49E-02	5.59E-03	2.10E+00
	Itu		9	1.86E-01	3.21E-01	7.50E-04	1.00E+00	3.14E-02	1.06E+01
	Geregu	Ce	9	2.87E+00	3.33E+00	2.35E-02	7.54E+00	4.92E-01	1.29E+01
	Itu		9	1.33E+00	3.10E+00	6.96E-03	9.53E+00	1.58E-01	9.69E+00
	Geregu	Eu	9	3.33E-02	3.17E-02	3.63E-03	1.11E-01	2.29E-02	2.67E+00
	Itu		9	4.07E-02	6.28E-02	1.84E-03	1.61E-01	1.30E-02	5.05E+00
	Geregu	Mo	9	2.25E-01	3.51E-01	5.56E-03	9.20E-01	5.75E-02	6.44E+00
	Itu		9	3.08E-01	2.25E-01	8.62E-02	8.09E-01	2.47E-01	2.03E+00
Grass	Geregu	Cs	5	1.67E-02	1.60E-03	1.54E-02	1.94E-02	1.67E-02	1.10E+00
	Itu		5	9.03E-02	4.52E-02	3.50E-02	1.59E-01	8.08E-02	1.73E+00

	Geregu	Se	5	1.43E-02	1.55E-02	3.79E-03	4.14E-02	9.78E-03	2.49E+00
Wildlife	**Location**	**Elements**	**N**	**AM**	**ASD**	**GM**	**GSD**	**Min**	**Max**
	Itu		5	3.06E-01	5.33E-01	1.60E-02	1.25E+00	8.12E-02	6.15E+00
	Geregu	Sr	5	7.50E-01	1.03E+00	4.13E-02	2.53E+00	2.69E-01	6.08E+00
	Itu		5	6.29E-01	1.34E+00	2.62E-02	3.03E+00	7.30E-02	8.05E+00
	Geregu	Co	5	1.90E-01	9.81E-02	7.50E-02	3.33E-01	1.69E-01	1.76E+00
	Itu		5	1.17E+00	1.59E+00	3.11E-01	4.00E+00	6.87E-01	2.76E+00
	Geregu	U	5	1.46E-02	1.24E-02	5.73E-03	3.60E-02	1.16E-02	2.07E+00
	Itu		5	5.60E-02	6.59E-02	8.93E-03	1.51E-01	2.68E-02	4.06E+00
	Geregu	Th	5	3.40E-03	2.71E-03	1.41E-03	7.88E-03	2.71E-03	2.07E+00
	Itu		5	1.48E-01	1.26E-01	8.73E-03	2.40E-01	6.73E-02	5.72E+00
	Geregu	Ce	5	8.59E-02	9.26E-02	1.39E-02	2.47E-01	5.62E-02	2.82E+00
	Itu		5	2.66E-01	3.35E-01	4.61E-02	8.17E-01	1.33E-01	3.72E+00
	Geregu	Eu	5	1.69E-02	1.32E-02	3.94E-03	3.69E-02	1.25E-02	2.51E+00
	Itu		5	7.47E-02	7.85E-02	1.25E-02	2.03E-01	4.69E-02	3.00E+00
	Geregu	Mo	5	6.43E-02	4.40E-02	1.10E-02	1.13E-01	4.79E-02	2.64E+00
	Itu		5	3.33E-01	3.49E-01	9.12E-02	9.37E-01	2.31E-01	2.51E+00
Rat	Geregu	Cs	1	6.83E-02	.	6.83E-02	6.83E-02	6.83E-02	
	Itu		4	1.56E-01	5.05E-02	1.11E-01	2.28E-01	1.50E-01	1.35E+00
	Geregu	Se	1	2.09E-02	.	2.09E-02	2.09E-02	2.09E-02	
	Itu		4	2.38E-01	1.08E-01	1.28E-01	3.71E-01	2.20E-01	1.60E+00
	Geregu	Sr	1	1.88E+00	.	1.88E+00	1.88E+00	1.88E+00	
	Itu		4	1.05E+00	1.05E-01	8.93E-01	1.12E+00	1.04E+00	1.11E+00
	Geregu	Co	1	4.05E-02	.	4.05E-02	4.05E-02	4.05E-02	
	Itu		4	8.64E-01	1.19E+00	1.59E-01	2.64E+00	4.37E-01	3.65E+00
	Geregu	U	1	1.02E-02	.	1.02E-02	1.02E-02	1.02E-02	
	Itu		4	7.46E-01	1.36E+00	1.84E-02	2.79E+00	1.12E-01	1.06E+01
	Geregu	Th	1	2.19E-03	.	2.19E-03	2.19E-03	2.19E-03	
	Itu		4	3.83E-01	4.25E-01	2.54E-02	1.00E+00	2.01E-01	4.59E+00
	Geregu	Ce	1	6.17E-02	.	6.17E-02	6.17E-02	6.17E-02	
	Itu		4	4.30E+00	4.93E+00	7.16E-02	9.35E+00	7.97E-01	1.54E+01

	Geregu	Eu	1	8.18E-03	.		8.18E-03	8.18E-03	8.18E-03	
Wildlife	**Location**	**Elements**	**N**	**AM**		**ASD**	**GM**	**GSD**	**Min**	**Max**
	Itu		4	2.81E-02		4.87E-03	2.40E-02	3.29E-02	2.78E-02	1.19E+00
	Geregu	Mo	1	2.47E-02	.		2.47E-02	2.47E-02	2.47E-02	
	Itu		4	4.65E-01		3.17E-01	1.28E-01	8.39E-01	3.71E-01	2.31E+00

Appendix 7. Concentration of stable elements in food crops (mg/kg DW) (Geregu vs Itu)

Crops	**Location**	**Elements**	**N**	**AM**	**ASD**	**Min**	**Max**	**GM**	**GSD**
Fruit	Geregu	Cs	5	1.16E-02	5.32E-03	5.00E-03	1.73E-02	1.05E-02	1.67E+00
	Itu	Cs	5	1.46E-02	1.02E-03	1.35E-02	1.60E-02	1.46E-02	1.07E+00
	Geregu	Se	5	2.55E-03	2.13E-03	1.30E-04	5.04E-03	1.33E-03	4.85E+00
	Itu	Se	5	4.39E-03	1.65E-03	2.22E-03	6.05E-03	4.11E-03	1.54E+00
	Geregu	Sr	5	2.18E-01	5.16E-02	1.35E-01	2.67E-01	2.12E-01	1.31E+00
	Itu	Sr	5	9.03E-02	1.16E-02	7.43E-02	1.04E-01	8.97E-02	1.14E+00
	Geregu	Co	5	3.83E-03	3.35E-03	1.86E-03	9.77E-03	3.08E-03	1.95E+00
	Itu	Co	5	1.04E-02	4.65E-03	6.30E-03	1.66E-02	9.58E-03	1.54E+00
	Geregu	U	5	1.90E-05	4.62E-06	1.00E-05	2.00E-05	1.85E-05	1.29E+00
	Itu	U	5	2.63E-05	5.53E-06	2.00E-05	3.00E-05	2.59E-05	1.24E+00
	Geregu	Th	5	2.34E-04	0.00E+00	2.30E-04	2.30E-04	2.34E-04	1.00E+00
	Itu	Th	5	2.34E-04	0.00E+00	2.30E-04	2.30E-04	2.34E-04	1.00E+00
	Geregu	Ce	5	1.60E-02	2.47E-03	1.31E-02	1.99E-02	1.58E-02	1.16E+00
	Itu	Ce	5	1.40E-02	8.17E-04	1.33E-02	1.54E-02	1.39E-02	1.06E+00
	Geregu	Eu	5	1.79E-05	5.77E-06	1.00E-05	2.00E-05	1.71E-05	1.42E+00
	Itu	Eu	5	7.40E-06	5.19E-06	0.00E+00	1.00E-05	5.60E-06	2.42E+00
	Geregu	Mo	5	1.13E-02	1.24E-02	3.00E-04	3.17E-02	5.18E-03	5.79E+00
	Itu	Mo	5	3.80E-03	3.52E-03	8.10E-04	9.57E-03	2.64E-03	2.68E+00

Maize	Geregu	Cs	5	1.02E-01	5.96E-02	3.61E-02	1.90E-01	8.73E-02	1.89E+00
	Itu	Cs	5	1.96E-01	7.28E-02	1.22E-01	3.12E-01	1.86E-01	1.43E+00
Wildlife	**Location**	**Elements**	**N**	**AM**	**ASD**	**GM**	**GSD**	**Min**	**Max**
	Geregu	Se	5	2.65E-02	1.13E-02	1.39E-02	4.19E-02	2.45E-02	1.58E+00
	Itu	Se	5	1.19E-01	7.24E-02	5.39E-03	2.01E-01	7.41E-02	4.41E+00
	Geregu	Sr	5	7.37E+00	1.47E+01	6.29E-01	3.37E+01	1.63E+00	5.50E+00
	Itu	Sr	5	9.00E+00	1.59E+01	1.11E-02	3.68E+01	4.88E-01	4.07E+01
	Geregu	Co	5	6.35E+00	4.79E+00	6.64E-01	1.29E+01	4.34E+00	3.17E+00
	Itu	Co	5	2.93E-01	5.75E-01	1.94E-02	1.32E+00	7.16E-02	5.29E+00
	Geregu	U	5	2.45E-04	0.00E+00	2.40E-04	2.40E-04	2.45E-04	1.00E+00
	Itu	U	5	2.45E-04	0.00E+00	2.40E-04	2.40E-04	2.45E-04	1.00E+00
	Geregu	Th	5	1.77E-01	1.89E-01	5.52E-02	5.13E-01	1.27E-01	2.29E+00
	Itu	Th	5	2.93E-03	1.52E-03	7.20E-04	4.39E-03	2.47E-03	2.09E+00
	Geregu	Ce	5	4.65E-02	4.11E-02	8.06E-03	1.14E-01	3.26E-02	2.72E+00
	Itu	Ce	5	7.50E-04	0.00E+00	7.50E-04	7.50E-04	7.50E-04	1.00E+00
	Geregu	Eu	5	3.26E-03	3.53E-04	2.82E-03	3.62E-03	3.25E-03	1.12E+00
	Itu	Eu	5	3.80E-03	5.45E-04	3.02E-03	4.43E-03	3.77E-03	1.16E+00
	Geregu	Mo	5	1.24E+00	0.00E+00	1.24E+00	1.24E+00	1.24E+00	1.00E+00
	Itu	Mo	5	1.24E+00	0.00E+00	1.24E+00	1.24E+00	1.24E+00	1.00E+00
Root	Geregu	Cs	5	9.81E-02	4.98E-02	3.72E-02	1.68E-01	8.71E-02	1.77E+00
	Itu	Cs	5	9.46E-02	2.07E-02	7.13E-02	1.27E-01	9.29E-02	1.24E+00
	Geregu	Se	5	1.11E-02	9.19E-03	7.00E-04	2.09E-02	6.60E-03	4.02E+00
	Itu	Se	5	2.99E-02	7.77E-03	2.11E-02	4.00E-02	2.91E-02	1.31E+00
	Geregu	Sr	5	3.74E+00	1.63E+00	2.29E+00	6.46E+00	3.50E+00	1.48E+00
	Itu	Sr	5	1.03E+00	4.99E-01	5.87E-01	1.86E+00	9.47E-01	1.55E+00
	Geregu	Co	5	4.21E-02	3.11E-02	1.44E-02	8.12E-02	3.26E-02	2.28E+00
	Itu	Co	5	3.48E-02	1.92E-02	1.44E-02	6.37E-02	3.07E-02	1.76E+00
	Geregu	U	5	1.67E-04	1.18E-04	8.00E-05	3.70E-04	1.40E-04	1.88E+00
	Itu	U	5	1.25E-04	7.28E-05	5.00E-05	2.10E-04	1.09E-04	1.82E+00
	Geregu	Th	5	1.56E-03	0.00E+00	1.56E-03	1.56E-03	1.56E-03	1.00E+00
	Itu	Th	5	1.56E-03	0.00E+00	1.56E-03	1.56E-03	1.56E-03	1.00E+00

	Geregu	Ce	5	1.77E-01	1.20E-01	1.12E-01	3.91E-01	1.55E-01	1.69E+00
	Itu	Ce	5	1.00E-01	2.72E-02	6.92E-02	1.41E-01	9.72E-02	1.31E+00
Wildlife	**Location**	**Elements**	**N**	**AM**	**ASD**	**GM**	**GSD**	**Min**	**Max**
	Itu	Eu	5	7.45E-05	3.60E-05	4.00E-05	1.20E-04	6.75E-05	1.66E+00
	Geregu	Mo	5	6.06E-02	5.58E-02	2.82E-03	1.32E-01	3.26E-02	4.62E+00
	Itu	Mo	5	9.17E-02	5.99E-02	3.82E-03	1.57E-01	5.55E-02	4.61E+00
Vegetable	Geregu	Cs	5	1.15E-01	4.42E-02	7.53E-02	1.78E-01	1.08E-01	1.46E+00
	Itu	Cs	5	1.04E-01	6.79E-03	9.72E-02	1.11E-01	1.04E-01	1.07E+00
	Geregu	Se	5	1.50E-02	6.94E-03	9.44E-03	2.67E-02	1.40E-02	1.51E+00
	Itu	Se	5	3.29E-02	1.36E-02	1.95E-02	5.58E-02	3.10E-02	1.46E+00
	Geregu	Sr	5	1.40E+01	9.70E+00	6.35E-01	2.29E+01	8.33E+00	4.55E+00
	Itu	Sr	5	7.51E+00	4.92E+00	1.94E+00	1.25E+01	5.78E+00	2.43E+00
	Geregu	Co	5	8.44E-02	4.12E-02	1.44E-02	1.19E-01	6.84E-02	2.41E+00
	Itu	Co	5	1.55E-01	1.60E-01	5.23E-02	4.37E-01	1.13E-01	2.26E+00
	Geregu	U	5	2.45E-04	6.89E-05	1.40E-04	3.40E-04	2.37E-04	1.36E+00
	Itu	U	5	1.02E-04	6.11E-05	1.00E-05	1.80E-04	7.41E-05	3.09E+00
	Geregu	Th	5	1.62E-03	1.44E-04	1.56E-03	1.88E-03	1.62E-03	1.09E+00
	Itu	Th	5	1.56E-03	0.00E+00	1.56E-03	1.56E-03	1.56E-03	1.00E+00
	Geregu	Ce	5	1.27E-01	3.04E-02	1.07E-01	1.80E-01	1.24E-01	1.24E+00
	Itu	Ce	5	8.95E-02	7.90E-03	7.95E-02	9.64E-02	8.92E-02	1.09E+00
	Geregu	Eu	5	1.39E-04	5.95E-05	7.00E-05	2.20E-04	1.29E-04	1.56E+00
	Itu	Eu	5	4.17E-05	3.79E-05	1.00E-05	1.00E-04	2.87E-05	2.70E+00
	Geregu	Mo	5	3.76E-02	7.13E-02	1.41E-03	1.65E-01	9.62E-03	5.73E+00
	Itu	Mo	5	9.78E-02	5.86E-02	3.05E-02	1.49E-01	7.96E-02	2.18E+00
Cereal	Geregu	Cs	5	9.06E-02	2.89E-02	6.98E-02	1.37E-01	8.73E-02	1.34E+00
	Geregu	Se	5	2.32E-02	7.03E-03	1.76E-02	3.11E-02	2.24E-02	1.34E+00
	Geregu	Sr	5	3.98E+00	1.46E+00	2.33E+00	5.45E+00	3.74E+00	1.50E+00
	Geregu	Co	5	5.90E+00	6.23E-01	5.01E+00	6.77E+00	5.87E+00	1.11E+00
	Geregu	U	5	2.45E-04	0.00E+00	2.40E-04	2.40E-04	2.45E-04	1.00E+00
	Geregu	Th	5	2.31E+00	1.72E+00	1.37E+00	5.38E+00	1.98E+00	1.76E+00

	Geregu	Ce	5	2.98E-01	1.97E-02	2.67E-01	3.19E-01	2.97E-01	1.07E+00
	Geregu	Eu	5	1.67E-03	1.99E-04	1.52E-03	1.90E-03	1.66E-03	1.12E+00
Wildlife	**Location**	**Elements**	**N**	**AM**	**ASD**	**GM**	**GSD**	**Min**	**Max**
	Geregu	Mo	5	6.18E-01	0.00E+00	6.18E-01	6.18E-01	6.18E-01	1.00E+00
Legume	Geregu	Cs	5	1.11E-01	3.17E-02	7.53E-02	1.52E-01	1.08E-01	1.33E+00
	Geregu	Se	5	2.85E-02	1.25E-02	1.26E-02	4.05E-02	2.58E-02	1.68E+00
	Geregu	Sr	5	1.93E+00	1.19E+00	4.68E-01	3.22E+00	1.54E+00	2.30E+00
	Geregu	Co	5	4.35E-02	9.72E-03	3.64E-02	6.03E-02	4.27E-02	1.22E+00
	Geregu	U	5	2.74E-04	1.60E-04	1.20E-04	4.50E-04	2.36E-04	1.86E+00
	Geregu	Th	5	1.56E-03	0.00E+00	1.56E-03	1.56E-03	1.56E-03	1.00E+00
	Geregu	Ce	5	2.40E-01	8.31E-02	1.36E-01	3.46E-01	2.28E-01	1.44E+00
	Geregu	Eu	5	2.87E-04	1.25E-04	1.10E-04	4.10E-04	2.59E-04	1.72E+00
	Geregu	Mo	5	6.56E-02	8.02E-02	4.00E-04	1.84E-01	1.29E-02	1.50E+01

Appendix 8. Stable elements concentration in soil (mg/kg DW) (Geregu vs Itu)

Soil	**Location**	**Elements**	**N**	**AM**	**ASD**	**Min**	**Max**	**GM**	**GSD**
Fruit	Geregu	Cs	5	9.82E-01	2.53E-01	7.01E-01	1.24E+00	9.54E-01	1.31E+00
	Itu	Cs	5	4.26E-01	4.00E-02	3.64E-01	4.71E-01	4.24E-01	1.10E+00
	Geregu	Se	5	5.57E-01	5.18E-01	1.85E-01	1.43E+00	4.10E-01	2.35E+00
	Itu	Se	5	7.09E-01	1.47E-01	6.21E-01	9.62E-01	6.98E-01	1.21E+00
	Geregu	Sr	5	4.23E+00	2.29E+00	1.78E+00	7.04E+00	3.70E+00	1.83E+00
	Itu	Sr	5	1.46E+00	8.16E-01	1.05E-01	2.30E+00	1.00E+00	3.58E+00
	Geregu	Co	5	9.31E-02	4.19E-02	2.81E-02	1.32E-01	8.22E-02	1.88E+00
	Itu	Co	5	5.27E-02	5.16E-02	6.62E-03	1.36E-01	3.31E-02	3.21E+00
	Geregu	U	5	1.62E-02	7.27E-03	7.03E-03	2.52E-02	1.47E-02	1.67E+00
	Itu	U	5	7.29E-03	3.40E-03	1.72E-03	9.58E-03	6.21E-03	2.09E+00

	Geregu	Th	5	1.84E-01	8.15E-02	7.09E-02	2.95E-01	1.67E-01	1.70E+00
	Itu	Th	5	4.16E-02	2.65E-02	1.56E-03	6.65E-02	2.46E-02	4.85E+00

Soil	**Location**	**Elements**	**N**	**AM**	**ASD**	**Min**	**Max**	**GM**	**GSD**
	Geregu	Ce	5	5.93E-01	4.51E-01	1.91E-02	1.24E+00	3.31E-01	5.19E+00
	Itu	Ce	5	6.80E-01	4.08E-01	4.87E-03	9.66E-01	2.98E-01	1.01E+01
	Geregu	Eu	5	6.00E-03	3.12E-03	1.50E-03	9.72E-03	5.08E-03	2.07E+00
	Itu	Eu	5	1.15E-03	3.00E-04	6.80E-04	1.51E-03	1.11E-03	1.35E+00
	Geregu	Mo	5	1.66E-01	9.19E-02	6.54E-02	2.65E-01	1.41E-01	1.96E+00
	Itu	Mo	5	3.35E-02	6.80E-03	3.05E-02	4.57E-02	3.30E-02	1.20E+00
Maize	Geregu	Cs	5	1.11E+00	2.50E-01	7.93E-01	1.39E+00	1.09E+00	1.27E+00
	Itu	Cs	4	4.24E-01	4.39E-02	3.68E-01	4.75E-01	4.22E-01	1.11E+00
	Geregu	Se	5	2.14E-02	7.91E-03	1.41E-02	3.12E-02	2.03E-02	1.44E+00
	Itu	Se	5	2.67E-02	6.21E-03	2.09E-02	3.60E-02	2.62E-02	1.25E+00
	Geregu	Sr	5	1.20E+01	0.00E+00	1.20E+01	1.20E+01	1.20E+01	1.00E+00
	Itu	Sr	5	1.20E+01	0.00E+00	1.20E+01	1.20E+01	1.20E+01	1.00E+00
	Geregu	Co	5	1.56E-01	1.66E-01	3.97E-02	4.02E-01	9.30E-02	3.12E+00
	Itu	Co	5	2.07E-01	9.00E-02	7.07E-02	3.03E-01	1.85E-01	1.78E+00
	Geregu	U	5	5.78E-03	7.45E-03	1.33E-03	1.87E-02	3.24E-03	3.13E+00
	Itu	U	5	4.28E-05	1.38E-05	3.00E-05	6.00E-05	4.09E-05	1.41E+00
	Geregu	Th	5	4.17E-02	4.76E-02	8.67E-03	1.21E-01	2.52E-02	3.00E+00
	Itu	Th	5	2.04E-03	3.86E-04	1.59E-03	2.34E-03	2.01E-03	1.22E+00
	Geregu	Ce	5	9.66E-01	1.05E-01	8.35E-01	1.07E+00	9.62E-01	1.12E+00
	Itu	Ce	5	1.13E+00	1.62E-01	8.95E-01	1.31E+00	1.12E+00	1.16E+00
	Geregu	Eu	5	4.35E-02	6.84E-02	1.51E-03	1.59E-01	7.83E-03	9.87E+00
	Itu	Eu	5	4.99E-01	6.84E-01	1.51E-03	1.34E+00	2.21E-02	3.96E+01
	Geregu	Mo	5	4.06E-01	3.75E-01	1.38E-01	1.06E+00	3.09E-01	2.18E+00
	Itu	Mo	5	3.05E-01	0.00E+00	3.05E-01	3.05E-01	3.05E-01	1.00E+00
Root	Geregu	Cs	5	1.16E+00	1.88E-01	1.00E+00	1.46E+00	1.15E+00	1.17E+00
	Itu	Cs	4	4.03E-01	2.32E-02	3.70E-01	4.19E-01	4.03E-01	1.06E+00
	Geregu	Se	5	2.60E-01	6.37E-02	1.66E-01	3.42E-01	2.54E-01	1.30E+00

	Itu	Se	5	3.74E-01	6.30E-01	9.20E-02	1.50E+00	1.61E-01	3.49E+00
	Geregu	Sr	5	5.03E+00	1.56E+00	2.41E+00	6.31E+00	4.77E+00	1.48E+00
	Itu	Sr	5	1.79E-01	3.05E-01	1.11E-02	7.21E-01	5.48E-02	5.62E+00
Soil	**Location**	**Elements**	**N**	**AM**	**ASD**	**Min**	**Max**	**GM**	**GSD**
	Geregu	Co	5	2.49E-01	8.21E-02	1.76E-01	3.76E-01	2.40E-01	1.36E+00
	Itu	Co	5	6.88E-02	4.12E-02	3.97E-02	1.27E-01	6.00E-02	1.78E+00
	Geregu	U	5	2.21E-02	4.30E-03	1.47E-02	2.58E-02	2.17E-02	1.25E+00
	Itu	U	5	3.83E-03	4.17E-03	1.10E-04	8.66E-03	1.24E-03	8.09E+00
	Geregu	Th	5	2.65E-01	6.49E-02	1.57E-01	3.18E-01	2.57E-01	1.33E+00
	Itu	Th	5	1.25E-02	2.45E-02	1.56E-03	5.64E-02	3.19E-03	4.98E+00
	Geregu	Ce	5	2.06E+00	4.29E-01	1.37E+00	2.48E+00	2.02E+00	1.26E+00
	Itu	Ce	5	1.82E-01	3.96E-01	4.87E-03	8.91E-01	1.38E-02	1.03E+01
	Geregu	Eu	5	4.77E-03	1.12E-03	2.97E-03	5.86E-03	4.65E-03	1.31E+00
	Itu	Eu	5	1.42E-03	1.97E-04	1.06E-03	1.51E-03	1.40E-03	1.17E+00
	Geregu	Mo	5	1.15E-01	6.93E-02	6.16E-02	2.08E-01	1.00E-01	1.80E+00
	Itu	Mo	5	4.10E-02	3.80E-02	1.41E-02	1.08E-01	3.15E-02	2.13E+00
Vegetable	Geregu	Cs	5	1.01E+00	2.59E-01	7.14E-01	1.30E+00	9.80E-01	1.31E+00
	Itu	Cs	5	4.56E-01	4.63E-02	3.99E-01	5.26E-01	4.54E-01	1.11E+00
	Geregu	Se	5	3.03E-01	6.22E-02	2.43E-01	3.79E-01	2.98E-01	1.22E+00
	Itu	Se	5	4.20E-01	2.06E-01	9.20E-02	5.97E-01	3.52E-01	2.17E+00
	Geregu	Sr	5	6.40E+00	2.82E+00	1.76E+00	8.77E+00	5.60E+00	1.94E+00
	Itu	Sr	5	1.20E+00	6.53E-01	4.86E-02	1.64E+00	7.52E-01	4.63E+00
	Geregu	Co	5	2.54E-01	1.09E-01	7.17E-02	3.60E-01	2.23E-01	1.91E+00
	Itu	Co	5	3.97E-02	0.00E+00	3.97E-02	3.97E-02	3.97E-02	1.00E+00
	Geregu	U	5	2.21E-02	8.62E-03	8.44E-03	3.09E-02	2.03E-02	1.67E+00
	Itu	U	5	1.02E-02	5.71E-03	1.10E-04	1.39E-02	4.91E-03	8.42E+00
	Geregu	Th	5	2.57E-01	1.28E-01	4.82E-02	3.85E-01	2.10E-01	2.32E+00
	Itu	Th	5	6.94E-02	3.80E-02	1.56E-03	9.09E-02	3.87E-02	6.02E+00
	Geregu	Ce	5	2.23E+00	9.23E-01	8.09E-01	3.26E+00	2.02E+00	1.72E+00
	Itu	Ce	5	1.01E+00	5.51E-01	3.29E-02	1.35E+00	6.06E-01	5.10E+00
	Geregu	Eu	5	4.62E-03	2.20E-03	1.04E-03	6.73E-03	3.91E-03	2.13E+00

	Itu	Eu	5	1.49E-03	3.76E-05	1.42E-03	1.51E-03	1.49E-03	1.03E+00
	Geregu	Mo	5	1.23E-01	6.35E-02	7.34E-02	2.17E-01	1.11E-01	1.63E+00
	Itu	Mo	5	1.05E-01	7.60E-02	3.05E-02	1.95E-01	7.91E-02	2.44E+00
Soil	**Location**	**Elements**	**N**	**AM**	**ASD**	**Min**	**Max**	**GM**	**GSD**
Cereal	Geregu	Cs	5	1.20E+00	1.33E-01	9.89E-01	1.36E+00	1.19E+00	1.12E+00
	Geregu	Se	5	4.89E-03	1.28E-03	2.97E-03	6.42E-03	4.74E-03	1.34E+00
	Geregu	Sr	5	5.96E+00	0.00E+00	5.96E+00	5.96E+00	5.96E+00	1.00E+00
	Geregu	Co	5	2.74E-01	1.22E-01	8.44E-02	4.20E-01	2.42E-01	1.85E+00
	Geregu	U	5	4.46E-02	3.24E-03	3.88E-02	4.65E-02	4.45E-02	1.08E+00
	Geregu	Th	5	8.50E-02	7.77E-02	1.19E-03	1.62E-01	2.29E-02	1.20E+01
	Geregu	Ce	5	9.95E-01	1.18E-01	9.05E-01	1.13E+00	9.90E-01	1.12E+00
	Geregu	Eu	5	6.35E-03	7.43E-04	5.46E-03	7.17E-03	6.32E-03	1.13E+00
	Geregu	Mo	5	3.27E-01	1.05E-01	2.00E-01	4.36E-01	3.12E-01	1.42E+00
Legume	Geregu	Cs	5	1.16E+00	3.21E-01	6.29E-01	1.40E+00	1.12E+00	1.40E+00
	Geregu	Se	5	1.26E+00	1.97E+00	9.24E-02	4.74E+00	4.79E-01	4.62E+00
	Geregu	Sr	5	5.56E+00	4.33E+00	2.32E+00	1.29E+01	4.51E+00	2.02E+00
	Geregu	Co	5	3.50E-01	1.41E-01	1.53E-01	5.36E-01	3.23E-01	1.60E+00
	Geregu	U	5	8.42E-03	1.05E-02	1.07E-03	2.50E-02	3.80E-03	4.26E+00
	Geregu	Th	5	1.14E-01	1.12E-01	1.52E-02	2.96E-01	7.20E-02	3.16E+00
	Geregu	Ce	5	7.47E-01	1.15E+00	4.87E-03	2.62E+00	5.07E-02	2.51E+01
	Geregu	Eu	5	2.16E-03	1.79E-03	8.30E-04	5.10E-03	1.68E-03	2.17E+00
	Geregu	Mo	5	1.05E-01	7.36E-02	5.67E-02	2.31E-01	8.96E-02	1.80E+00

Appendix 9. Concentration ratios of stable elements in food crops from case study locations

Crops	**Location**	**Elements**	**N**	**AM**	**ASD**	**Min**	**Max**	**GM**	**GSD**
Fruit	Geregu	Cs	5	1.19E-02	4.11E-03	4.70E-03	1.48E-02	1.11E-02	1.62E+00
	Itu	Cs	5	3.46E-02	4.21E-03	3.06E-02	4.04E-02	3.44E-02	1.13E+00

	Geregu	Se	5	5.92E-03	6.64E-03	7.00E-04	1.65E-02	3.25E-03	3.61E+00
	Itu	Se	5	6.18E-03	2.11E-03	3.58E-03	8.49E-03	5.88E-03	1.43E+00
	Geregu	Sr	5	6.94E-02	4.88E-02	3.14E-02	1.43E-01	5.73E-02	1.97E+00
	Itu	Sr	5	2.25E-01	3.88E-01	3.23E-02	9.19E-01	8.93E-02	3.77E+00
Crops	**Location**	**Elements**	**N**	**AM**	**ASD**	**Min**	**Max**	**GM**	**GSD**
	Geregu	Co	5	8.73E-02	1.45E-01	1.63E-02	3.47E-01	3.75E-02	3.58E+00
	Itu	Co	5	4.85E-01	4.61E-01	4.62E-02	1.14E+00	2.90E-01	3.57E+00
	Geregu	U	5	1.30E-03	3.65E-04	9.50E-04	1.85E-03	1.26E-03	1.31E+00
	Itu	U	5	4.90E-03	3.76E-03	3.07E-03	1.16E-02	4.16E-03	1.78E+00
	Geregu	Th	5	1.58E-03	9.88E-04	7.90E-04	3.30E-03	1.40E-03	1.70E+00
	Itu	Th	5	3.40E-02	6.49E-02	3.51E-03	1.50E-01	9.48E-03	4.85E+00
	Geregu	Ce	5	1.85E-01	3.59E-01	1.60E-02	8.27E-01	4.78E-02	5.06E+00
	Itu	Ce	5	5.67E-01	1.23E+00	1.41E-02	2.77E+00	4.69E-02	9.92E+00
	Geregu	Eu	5	5.03E-03	5.32E-03	1.21E-03	1.42E-02	3.36E-03	2.69E+00
	Itu	Eu	5	7.34E-03	6.61E-03	1.84E-03	1.73E-02	5.05E-03	2.71E+00
	Geregu	Mo	5	1.27E-01	2.02E-01	1.47E-03	4.85E-01	3.67E-02	8.22E+00
	Itu	Mo	5	1.04E-01	7.52E-02	2.68E-02	2.09E-01	7.99E-02	2.37E+00
Maize	Geregu	Cs	5	8.67E-02	3.70E-02	4.55E-02	1.37E-01	8.01E-02	1.58E+00
	Itu	Cs	4	4.81E-01	1.33E-01	3.33E-01	6.56E-01	4.67E-01	1.32E+00
	Geregu	Se	5	1.47E+00	1.02E+00	4.90E-01	2.97E+00	1.21E+00	2.05E+00
	Itu	Se	5	4.96E+00	3.59E+00	1.81E-01	9.58E+00	2.83E+00	4.95E+00
	Geregu	Sr	5	6.14E-01	1.23E+00	5.25E-02	2.81E+00	1.35E-01	5.50E+00
	Itu	Sr	5	7.50E-01	1.32E+00	9.30E-04	3.07E+00	4.07E-02	4.07E+01
	Geregu	Co	5	1.65E-01	1.31E-01	6.59E-02	3.88E-01	1.33E-01	3.27E+00
	Itu	Co	5	2.303064	2.265505	0.833333	6.095975	1.640804	4.63E+00
	Geregu	U	5	1.10E-01	7.69E-02	1.31E-02	1.84E-01	7.56E-02	3.13E+00
	Itu	U	5	6.28E+00	2.21E+00	4.21E+00	9.17E+00	5.98E+00	1.41E+00
	Geregu	Th	5	5.84E+00	3.60E+00	2.19E+00	1.15E+01	5.02E+00	1.86E+00
	Itu	Th	5	1.46E+00	8.67E-01	4.39E-01	2.69E+00	1.23E+00	2.00E+00
	Geregu	Ce	5	4.62E-02	3.74E-02	8.56E-03	1.06E-01	3.39E-02	2.57E+00
	Itu	Ce	5	6.77E-04	1.05E-04	5.70E-04	8.40E-04	6.71E-04	1.16E+00

	Geregu	Eu	5	1.33E+00	1.18E+00	2.28E-02	2.40E+00	4.15E-01	9.89E+00
	Itu	Eu	5	1.53E+00	1.43E+00	3.00E-03	2.94E+00	1.71E-01	3.97E+01
	Geregu	Mo	5	4.92E+00	3.00E+00	1.17E+00	8.98E+00	4.02E+00	2.18E+00
	Itu	Mo	5	4.08E+00	0.00E+00	4.08E+00	4.08E+00	4.08E+00	1.00E+00
Crops	**Location**	**Elements**	**N**	**AM**	**ASD**	**Min**	**Max**	**GM**	**GSD**
Root	Geregu	Cs	5	8.76E-02	4.57E-02	2.54E-02	1.52E-01	7.56E-02	1.95E+00
	Itu	Cs	4	2.16E-01	3.99E-02	1.70E-01	2.57E-01	2.13E-01	1.21E+00
	Geregu	Se	5	4.73E-02	4.78E-02	2.78E-03	1.24E-01	2.60E-02	4.22E+00
	Itu	Se	5	2.43E-01	1.34E-01	2.67E-02	3.63E-01	1.81E-01	2.97E+00
	Geregu	Sr	5	7.73E-01	2.73E-01	4.41E-01	1.14E+00	7.33E-01	1.44E+00
	Itu	Sr	5	3.19E+01	2.67E+01	1.25E+00	6.51E+01	1.73E+01	4.94E+00
	Geregu	Co	5	1.68E-01	1.22E-01	7.44E-02	3.17E-01	1.36E-01	2.07E+00
	Itu	Co	5	5.90E-01	6.23E-01	1.11E-02	1.61E+00	2.55E-01	6.75E+00
	Geregu	U	5	7.37E-03	4.57E-03	3.34E-03	1.52E-02	6.47E-03	1.73E+00
	Itu	U	5	4.72E-01	8.00E-01	1.01E-02	1.87E+00	8.76E-02	9.21E+00
	Geregu	Th	5	6.29E-03	2.09E-03	4.89E-03	9.93E-03	6.06E-03	1.33E+00
	Itu	Th	5	8.06E-01	4.35E-01	2.76E-02	1.00E+00	4.88E-01	4.98E+00
	Geregu	Ce	5	8.93E-02	6.18E-02	4.77E-02	1.96E-01	7.68E-02	1.78E+00
	Itu	Ce	5	1.63E+01	1.06E+01	1.17E-01	2.89E+01	7.04E+00	1.01E+01
	Geregu	Eu	5	4.38E-02	2.86E-02	1.82E-02	8.60E-02	3.68E-02	1.95E+00
	Itu	Eu	5	5.52E-02	3.16E-02	2.36E-02	9.67E-02	4.80E-02	1.81E+00
	Geregu	Mo	5	4.61E-01	2.64E-01	3.84E-02	7.69E-01	3.26E-01	3.35E+00
	Itu	Mo	5	3.15E+00	2.35E+00	1.26E-01	5.39E+00	1.76E+00	4.89E+00
Vegetable	Geregu	Cs	5	1.14E-01	2.93E-02	7.17E-02	1.44E-01	1.10E-01	1.33E+00
	Itu	Cs	5	2.29E-01	1.38E-02	2.10E-01	2.45E-01	2.28E-01	1.06E+00
	Geregu	Se	5	5.39E-02	3.39E-02	2.63E-02	1.10E-01	4.69E-02	1.76E+00
	Itu	Se	5	1.01E-01	6.45E-02	4.72E-02	2.12E-01	8.81E-02	1.74E+00
	Geregu	Sr	5	2.02E+00	1.39E+00	3.61E-01	3.63E+00	1.49E+00	2.67E+00
	Itu	Sr	5	5.51E+01	1.14E+02	1.34E+00	2.58E+02	7.69E+00	8.36E+00
	Geregu	Co	5	3.13E-01	6.54E-02	2.01E-01	3.60E-01	3.06E-01	1.27E+00
	Itu	Co	5	3.90E+00	4.03E+00	1.32E+00	1.10E+01	2.84E+00	2.26E+00

	Geregu	U	5	1.38E-02	1.01E-02	7.01E-03	3.14E-02	1.17E-02	1.82E+00
	Itu	U	5	1.90E-01	4.06E-01	8.20E-04	9.16E-01	1.51E-02	1.27E+01
	Geregu	Th	5	1.20E-02	1.51E-02	4.05E-03	3.90E-02	7.69E-03	2.52E+00
	Itu	Th	5	2.14E-01	4.39E-01	1.71E-02	1.00E+00	4.03E-02	6.02E+00
Crops	**Location**	**Elements**	**N**	**AM**	**ASD**	**Min**	**Max**	**GM**	**GSD**
	Geregu	Ce	5	8.07E-02	7.96E-02	3.28E-02	2.22E-01	6.13E-02	2.11E+00
	Itu	Ce	5	5.42E-01	1.05E+00	6.12E-02	2.42E+00	1.47E-01	4.80E+00
	Geregu	Eu	5	6.08E-02	8.66E-02	1.06E-02	2.15E-01	3.30E-02	3.08E+00
	Itu	Eu	5	2.83E-02	2.58E-02	5.76E-03	6.67E-02	1.93E-02	2.75E+00
	Geregu	Mo	5	2.48E-01	4.37E-01	1.92E-02	1.03E+00	8.65E-02	4.45E+00
	Itu	Mo	5	1.03E+00	2.22E-01	7.63E-01	1.28E+00	1.01E+00	1.25E+00
Cereal	Geregu	Cs	5	7.61E-02	2.30E-02	5.76E-02	1.02E-01	7.34E-02	1.34E+00
	Geregu	Se	5	2.84E-02	6.60E-03	1.75E-02	3.49E-02	2.76E-02	1.69E+00
	Geregu	Sr	5	6.79E-01	2.47E-01	3.44E-01	9.26E-01	6.38E-01	1.50E+00
	Geregu	Co	5	2.93E-01	1.73E-01	7.83E-02	5.10E-01	2.41E-01	1.99E+00
	Geregu	U	5	6.98E-02	2.97E-02	3.35E-02	1.06E-01	6.44E-02	1.08E+00
	Geregu	Th	5	1.33E-01	2.16E-01	1.93E-02	5.19E-01	5.72E-02	1.01E+01
	Geregu	Ce	5	2.75E-02	3.22E-03	2.37E-02	3.11E-02	2.74E-02	1.15E+00
	Geregu	Eu	5	5.30E-02	1.70E-02	3.24E-02	7.06E-02	2.63E-01	1.09E+00
	Geregu	Mo	5	3.82E+00	3.13E+00	1.09E+00	7.43E+00	2.76E+00	1.42E+00
Legume	Geregu	Cs	5	9.79E-02	1.91E-02	7.53E-02	1.20E-01	9.64E-02	1.22E+00
	Geregu	Se	5	1.38E-01	1.74E-01	2.67E-03	4.38E-01	5.39E-02	6.73E+00
	Geregu	Sr	5	6.37E-01	5.88E-01	3.62E-02	1.34E+00	3.41E-01	4.47E+00
	Geregu	Co	5	1.46E-01	7.50E-02	6.98E-02	2.67E-01	1.32E-01	1.64E+00
	Geregu	U	5	1.05E-01	9.82E-02	8.84E-03	2.58E-01	6.22E-02	3.71E+00
	Geregu	Th	5	3.58E-02	3.98E-02	5.26E-03	1.03E-01	2.16E-02	3.16E+00
	Geregu	Ce	5	2.61E+01	2.65E+01	8.36E-02	6.15E+01	4.50E+00	2.18E+01
	Geregu	Eu	5	1.96E-01	1.66E-01	5.92E-02	4.85E-01	5.06E-02	2.12E+00
	Geregu	Mo	5	5.51E-01	6.91E-01	6.02E-03	1.70E+00	1.44E-01	1.08E+01

Appendix 10. ERICA tier2 dose rate assessment results

Distance(km)	Total Dose Rate per organism [µGy h-1]				
	Flying Insect	Amphibian	Annelid	Grasses & Herbs	Mammal - small-burrowing
1	5.48E-03	1.46E-02	5.56E-03	1.01E-02	1.51E-02
2	2.85E-03	7.60E-03	2.92E-03	5.25E-03	7.84E-03
3	1.56E-03	4.17E-03	1.60E-03	2.88E-03	4.31E-03
4	9.79E-04	2.61E-03	1.00E-03	1.80E-03	2.70E-03
5	6.71E-04	1.79E-03	6.88E-04	1.24E-03	1.85E-03
6	4.89E-04	1.31E-03	5.02E-04	9.02E-04	1.35E-03
7	3.74E-04	9.97E-04	3.83E-04	6.89E-04	1.03E-03
8	2.95E-04	7.88E-04	3.03E-04	5.44E-04	8.13E-04
9	2.40E-04	6.39E-04	2.46E-04	4.42E-04	6.60E-04
10	1.97E-04	5.26E-04	2.00E-04	3.64E-04	5.43E-04
11	1.67E-04	4.47E-04	1.72E-04	3.09E-04	4.61E-04
12	1.43E-04	3.82E-04	1.47E-04	2.64E-04	3.95E-04
13	1.24E-04	3.31E-04	1.27E-04	2.29E-04	3.42E-04
14	1.09E-04	2.90E-04	1.11E-04	2.00E-04	2.99E-04
15	9.60E-05	2.56E-04	9.84E-05	1.77E-04	2.64E-04
16	8.54E-05	2.28E-04	8.76E-05	1.57E-04	2.35E-04
17	7.66E-05	2.04E-04	7.85E-05	1.41E-04	2.11E-04
18	6.91E-05	1.84E-04	7.08E-05	1.27E-04	1.90E-04
19	6.26E-05	1.67E-04	6.42E-05	1.15E-04	1.73E-04
20	5.71E-05	1.52E-04	5.86E-05	1.05E-04	1.57E-04

Appendix 11a. Posthoc (Duncan test) statistical results of significant difference in multiple variable ANOVA test for food crops

Element	Crop		Locations	N	Subset for alpha = 0.05	
					1	2
Co	Maize	Duncan a,b	IAEA	77	4.06E-02	
			SSAD	47	7.71E-01	
			GERITU	10		39.57973
			Sig.		8.93E-01	1
	Legume	Duncan a,b	IAEA	105	6.26E-02	
			SSAD	27	6.67E-02	
			GERITU	5		0.146069
			Sig.		9.10E-01	1
	Root	Duncan a,b	IAEA	16	1.54E-01	
			SSAD	138	3.30E-01	
			GERITU	10	3.79E-01	
			Sig.		2.59E-01	

Appendix 11b. Posthoc (Duncan test) statistical results of significant difference in multiple variable ANOVA test for food crops

Elements	Crops		Locations	N	Subset for alpha = 0.05	
					1	2
Cs	Root	Duncana,b	IAEA	93	7.41E-02	
			GERITU	9	1.45E-01	
			SSAD	7		0.307043
			Sig.		2.42E-01	1
Sr	Legume	Duncana,b	GERITU	5	6.37E-01	
			IAEA	148	2.00E+00	
			SSAD	3		3.586667
			Sig.		8.20E-02	1
U	Root	Duncana,b	SSAD	6	2.01E-02	
			IAEA	83	5.86E-02	
			GERITU	10		0.23981
			Sig.		6.55E-01	1
Sr	Vegetable	Duncana,b	IAEA	19	1.03E+00	
			SSAD	7	2.35E+00	
			GERITU	10	2.85E+01	
			Sig.		1.74E-01	

Appendix 11c. Posthoc (Duncan test) statistical results of significant difference in multiple variable ANOVA test for wildlife

Elements	Wildlife		Locations	N	Subset for alpha = 0.05	
					1	2
Co	Grass	Duncana,b	SSAD	30	0.025372	
			IAEA	57	0.045268	
			GERITU	10		0.678068
			Sig.		0.866	1
Mo	Grass	Duncana,b	GERITU	10	0.198842	
			SSAD	28	0.586502	0.586502
			IAEA	19		1.070062
			Sig.		0.194	0.107
Se	Mammal	Duncana,b	SSAD	40	0.004753	
			GERITU	5		0.194747
			IAEA	40		0.235737
			Sig.		1	0.574
U	Grasses	Duncana,b	IAEA	82	0.022916	

SSAD	4	0.027457
GERITU	10	0.035313
Sig.		0.489

Appendix 12. Summary of soil properties (Geregu and Itu)

Soil Properties	Location	Mean	SD	Min	Max
PH	Geregu	5.46	0.41	4.70	6.40
	Itu	4.67	0.34	4.10	5.30
Acidity	Geregu	1.48	1.15	0.60	5.80
	Itu	1.42	1.60	0.40	9.90
H+	Geregu	1.35	0.93	0.40	5.10
	Itu	1.28	1.18	0.40	7.40
Ca cmol/kg	Geregu	55.42	33.93	15.42	108.03
	Itu	17.39	7.45	2.30	25.70
K cmol/kg	Geregu	0.59	0.69	0.05	3.13
	Itu	0.21	0.18	0.05	0.78
C.E.C cmol/kg	Geregu	60.78	33.97	17.58	117.69
	Itu	19.69	7.39	4.73	29.02
%O.M	Geregu	2.14	1.96	0.15	9.00
	Itu	3.02	1.50	0.17	7.01
%Clay	Geregu	17.32	12.15	4.20	77.80
	Itu	18.07	5.10	6.00	26.40

Supplementary information 1

Ethical Approval

Application Checklist

Ref No: *Office Use Only*

STR1617-76 STR

Name of Applicant: Mr Rutase Doroh

Document	**Enclosed? (indicate appropriate response)**				**Date**	**Version No**
Application Form	Mandatory			If not required, please give a reason		
Risk Assessment Form	Yes				15/03/17	1
Participant Invitation Letter			Not required for this project	Animal subjects only		
Participant Information Sheet			Not required for this project	Animal subjects only		
Participant Consent Form			Not required for this project	Animal subjects only		
Participant Recruitment Material			Not required for this project	Animal subjects only		
Organisation Management Consent / Agreement Letter			It is required for this project	Letter of Introduction to collaborative University in Nigeria (Uyo, Kogi,		

				Ibadan & Delta, Geregu & Itu local government and community leader is being processed.		
Research Instrument – e.g. questionnaire			Laboratory analytical facilities required for this project	For elemental analysis of soil, plant & animal tissues will be undertaken using ICP-MS. Being processed for approval (Chevron Nigeria)		
Draft Interview Guide			Not required for this project	Animal subjects only		
National Research Ethics Committee consent			Not required for this project	Ethics provided by University		
Note: If the appropriate documents are not submitted with the application form then the application will be returned directly to the applicant and will need to be resubmitted at a later date thus delaying the approval process						

S&T-ResearchEthics <S&T-ResearchEthics@salford.ac.uk>
Mon 05/06/2017 09:29

- Wood Mike <M.D.Wood@salford.ac.uk>;
- Droh, Rutase Monday (PG) <R.M.Doroh@edu.salford.ac.uk>

Hi Mike,

Many thanks for this, ethical approval has now been granted.

Best Wishes,
Lauren